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Decommissioning of Offshore Wind Turbines

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TABLE OF CONTENT

Index of tables	ii
Index of figures	iii
1 Introduction	1
1.1 Objectives.....	1
1.2 Background.....	1
1.3 Project structure	3
2 Technical aspects of dismantling	4
2.1 Introduction	4
2.2 Components to be decommissioned	5
2.2.1 Wind turbines.....	5
2.2.2 Wind turbine foundations	6
2.2.3 Offshore sub-sea cabling.....	9
2.2.4 Offshore substations and support structures	10
2.2.5 Other elements	10
2.3 Technologies and Processes.....	10
2.3.1 Stages	10
2.3.2 Vessels and logistics	18
2.4 Existing cases.....	24
2.4.1 Comparative with Gas and Oil offshore structures.....	25
2.4.2 Vindeby.....	28
2.4.3 Kincardine.....	29
2.5 Lifetime extension and Re-powering	30
2.5.1 Lifetime extension.....	30
2.5.2 Re-powering	32
2.6 Decommissioning Programs.....	34
3 Environmental Aspects.....	37
4 Legal and Political Aspects	41
5 Economical Aspects.....	43
5.1 Summary of costs	43
5.2 Modelling of decommissioning costs.....	44
6 Conclusions	49
7 References.....	51

INDEX OF TABLES

Table 1. Examples of weights of main components of wind turbine.....	6
Table 2. Cumulative Market Share - Offshore Substructures.	8
Table 3. Strong points of floating structures.....	8
Table 4. Summary of the main characteristics and capabilities of installation vessels.	21
Table 5. Example of vessels used in offshore wind farm construction in Europe	22
Table 6. Legal options for decommissioning.....	25
Table 7. Main processes of decommissioning O&G installations.	27
Table 8. Main differences between O&G and offshore wind structures	27
Table 9. Decommissioning process of Vindeby.....	28
Table 10. Decommissioning process of Kincardine.....	29
Table 11. Indicative schedule for Kincardine decommissioning	29
Table 12. Summary of the decommissioning programmes available	36
Table 13. Total potential recyclable materials of a 60MW wind turbine	38
Table 14. Disposal options by component	39

INDEX OF FIGURES

Figure 1. European Offshore Wind power market evolution	2
Figure 2. Decommissioning year of wind farms in Europe.....	2
Figure 3. Components of an offshore simplified wind project	5
Figure 4. Main parts of wind turbine	6
Figure 5. Types of bottom fixed foundations.....	7
Figure 6. Cumulative Market Share - Offshore Substructures	7
Figure 7. Types of floating foundations for offshore wind turbines	8
Figure 8. Example of the electrical infrastructure of a wind farm	9
Figure 9. Decommissioning stages	11
Figure 10. Decision-making in turbine removal	12
Figure 11. Traditional offshore turbine decommissioning options.....	13
Figure 12. Alternative wind turbine removal method	13
Figure 13. Summary of material disposal.....	18
Figure 14. Main categorisation of installation vessels	19
Figure 15. Type of installation vessels.....	19
Figure 16. Range of liftboats	20
Figure 17. Range of jackup barges	20
Figure 18. Range of SPIVs	21
Figure 19. Decommissioning options for O&G projects.....	26
Figure 20. Decommissioning process summary.....	33
Figure 21. Decommissioning process for offshore wind turbines	34
Figure 22. Process for submission, approval and review of decommissioning programmes	35
Figure 23. Hierarchy of operations.....	37
Figure 24. Turbine parts, main materials and potential disposal methods	38
Figure 25. Most common routes for wind turbine materials.....	40
Figure 26. Most common routes for foundations materials.....	40
Figure 27. Decommissioning costs breakthrough	43
Figure 28. Influential decision-making factors on continuing operation of wind farm.	44

1 INTRODUCTION

When thinking about the energy field, it is pretty clear that the only viable and sustainable solution towards the future it is renewable and clean energy systems, maybe not exclusively, but to be implanted partially. Within this topic, one must acknowledge that the field that has advanced the most these last years and the one that has the more untapped potential yet, may be wind energy. Knowing that, and also taking into account that this topic has always been of highly interest for me as I believe it is a study field very attractive, this is a subject area to whom somehow I feel bound and the motivation to learn and educate myself more about the subject was enormous, so this project was an opportunity I could not turn down. After having finished this final degree thesis I can only conclude saying that this *journey* has only started: my motivation on the subject has done nothing but grow.

1.1 OBJECTIVES

The main objective of this project is to give a global vision on the process of decommissioning offshore structures, from the needed technologies to the process itself. Given that this is a relatively new issue within the offshore wind energy field, the main backing has been literature review on offshore gas and oil structures. Comparatives between the two fields will be seen, as well as recycling issues, materials, technologies, regulations and guidelines.

1.2 BACKGROUND

Wind energy is the key to a sustainable future.

Nowadays in Europe “wind energy is the second largest form of power generation capacity” (*WindEurope Annual Report, 2017*) only overtaken by gas, and overhead of coal, large hydro and even nuclear resources. The offshore wind development over the last years has been incredibly high, spreading quickly over Europe and then worldwide. When the first technologies started to appear in the 90s, the capacity of an offshore windfarm was 4MW. Nowadays, this number has multiplied by a factor of 20, or even 25. The initial key markets were placed in the Netherlands and Denmark, then at the beginning of 2000, huge growths took place in Danish and UK markets. At present day, the UK is the dominant country in terms of offshore wind activity, followed by China and the rest of European countries. Since some concepts are always better understood when given some values, *Figure 1* below shows the evolution of European installed wind power this last decade.

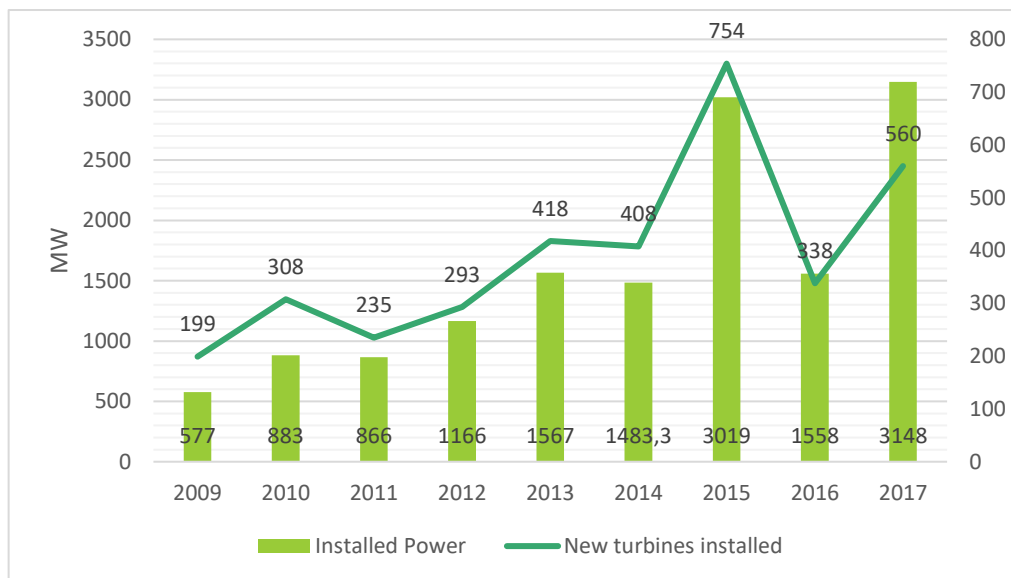


Figure 1. European Offshore Wind power market evolution. Data source: WindEurope (2009-2017)

The cumulative capacity for 2017 was 15.780 MW with 4.194 operating and grid-connected turbines. It is expected that Europe will have a total offshore wind capacity of 25GW by 2020 (*WindEurope Annual Report, 2017*) thanks to the 11 wind farms that are currently under construction. Needless to say, decommissioning of offshore wind farms will be a big issue during the next decades, as shows the prediction of existing plants to be decommissioned in Europe the following 30 years, seen in *Figure 2*.

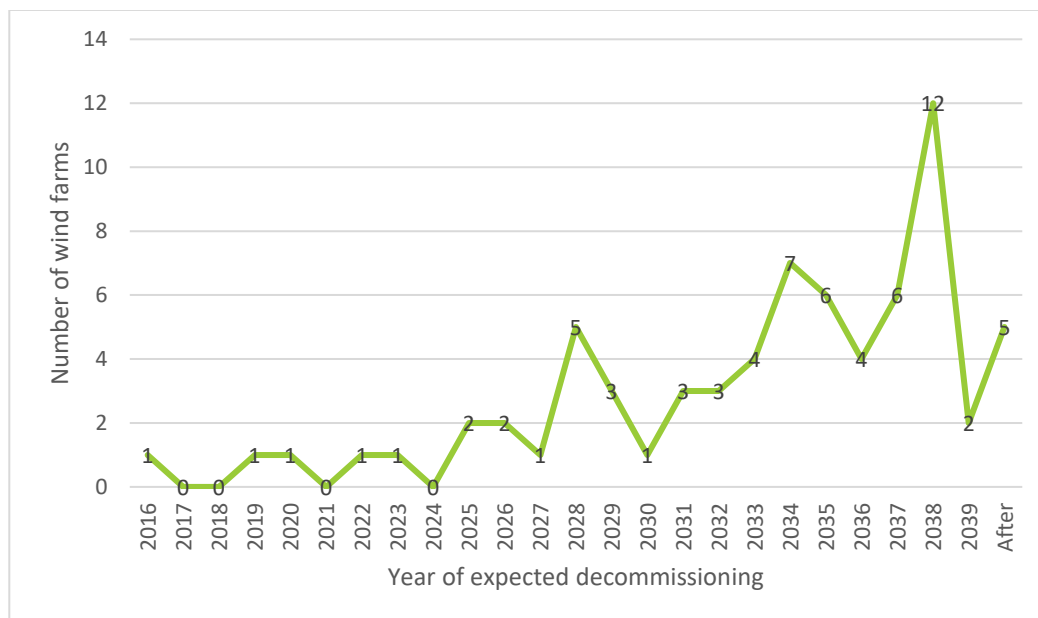


Figure 2. Decommissioning year of wind farms in Europe. Source: Topham & McMillan (2016)

1.3 PROJECT STRUCTURE

This project is conceived to give a basic and global vision on decommissioning offshore structures. For that purpose, the first section is oriented towards elementary knowledge of components of a wind farm and their materials. After that, the processes usually carried out will be reviewed, as well as the needed technologies to meet the needs of each operation. Further, a brief comparative between oil and gas structures and offshore wind farms will be seen, knowing that O&G industry has been the main reference and inspiration to this day in terms of technologies. Some real cases of actual dismantling of offshore wind farms will be then presented.

The final part of the report will give some hints on environmental, economical and legal aspects involving decommissioning wind turbines.

2 TECHNICAL ASPECTS OF DISMANTLING

2.1 INTRODUCTION

The decommissioning of a wind farm is understood as the inverse process of construction, the reverse of installation but less sensitive to component damage. Meaning that once the wind farm has reached its end-of-life and “*assuming any life-extension has already occurred*” (DNV-GL), the constitutive components must be removed. The technical lifetime of an offshore wind farm is 25-30 years, with possible extension, while the development time usually ranges from 7 to 10 years¹. The *but* of removal is mainly ensuring to “leave the site in similar conditions as before the deployment of the project” (Topham & McMillan, 2016) to preserve the safety of navigation, allow fishing and ultimately to protect the marine environment; whereas the *reason* of removal may be one of the following three:

- Components reach the end of their commercial life.
- Operation of the wind farm is no longer profitable.
- The permits that allowed the exploitation or safe operation of the area are not valid anymore.

Generally, dismantling should be taken into account at the very start of the project in order to decrease the impact and costs of the process. In many cases, a first decommissioning plan during the design stage of the farm is established, which will be modified and shaped up as the project moves forward. It would be also really interesting to contemplate the possibility of repowering or extending the life of the installation at early stages before complete removal. Anyhow, refurbishing is not always taken into account from the very beginning, but at the end of the farm lifetime.

By all means, offshore decommissioning can be understood as a combination of the onshore wind procedures to remove the elements and the technologies and vessels used in gas and oil infrastructures, as it requires to work in much more challenging ocean conditions. It is still a relatively new topic, as to this day operators and owners of offshore wind farms were more focused on improving installation efficiency and techniques than in developing decommissioning operations; so it is no surprise there are no standard methodologies or legislations implemented yet. This makes decommissioning a process with a large variety of options, ranging from complete removal to leaving structures in-situ. If installations are retrieved from the ocean it is really important to know if the components will be able to be re-used or recycled, or just disposed. On the other side, if the installations or structures are not completely removed, appropriate information of depth, location and dimensions must be given.

The type of technologies for dismantling –and obviously also the process– will vary in function of the wind farm. As it happens often in civil engineering, each project will be different, though in the background, basic features will be shared.

Elements taking part in the simplicity or, in contrast, in the complexity of the project are also wide ranging. Decommissioning, as well as commissioning of a wind farm, is subjected to uncontrollable factors, natural and climatological, such as storms or harsh waves; but overall, they can all be summarized. Platform stability will play an important role, the more stable the platform is, the easier to dismantle; and this is also subjected to sensitivity to waves. Distance from the coast or the port used as backup for the process also takes part, just as accessibility or

¹ European MSP Platform for the European Commission Directorate-General for Maritime Affairs and Fisheries

the existence of iced-zones near the wind turbines². In addition to the elements that can increase or decrease the costs, one must include the type of foundations or anchoring: the easiness for turbines to be un-tethered and floated back to shore makes that some kind of technologies may be more difficult to dismantle³.

2.2 COMPONENTS TO BE DECOMMISSIONED

Before starting to get into detail speaking strictly of the process of dismantling an offshore wind farm, one should first know the basic components that will need to be dismantled. This is the reason it has been found necessary presenting a brief description of the components and materials forming an offshore wind project along with its main characteristics.

Wind farms are not only formed by the wind turbines, but also by their foundations, the cabling, the offshore sub-stations, and finally the onshore substations, as seen in *Figure 3* below. In this section only components placed offshore will be studied.

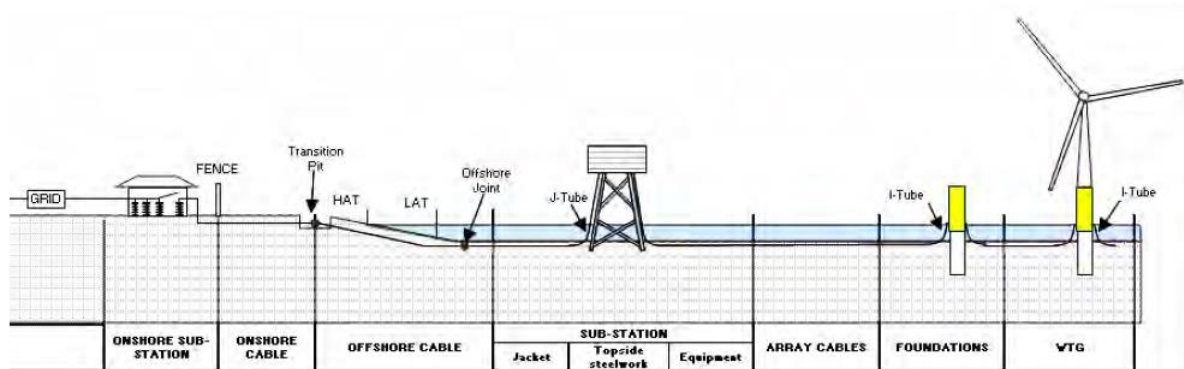


Figure 3. Components of an offshore simplified wind project. Source: OMECC (2016)

2.2.1 Wind turbines

Wind turbines are the components in charge of converting the kinetic energy of the wind into electrical energy, and they are constituted by several parts:

- **Nacelle**
Contains the assemblies (bearings, lubrication system, shafts, transformer, generator, power converter and brake system) of the wind turbine for power generation, and its housing is usually made of fiberglass. The whole ensemble is supported on a rigid bed plate made from steel.
- **Rotor**
Includes the hub, the blades and blade pitch system.
The turbine blades are hollow shells normally made of glass fiber and epoxy resin. Some critical areas may use carbon fiber, and sometimes they can even be made of aluminum, but this is not very common.

² This will affect not only structure stability but also accessibility, because barges depend of water plane area to reach their equilibrium.

³ In reference to spar buoys and TLP technologies for floating wind turbines.

- **Tower**

This steel lattice or tubular tower is the support to the turbine blades and nacelle. Generally made of structural steel and painted both inside and out for protection against corrosion. The relevant tower weight which will be important when choosing the vessel for decommissioning is shown in *Table 1* and includes the internal steelwork of the structure (that is to say comprising internal platforms, ladder and lift mechanism).

TURBINE TYPE	NACELLE	ROTOR BLADES	TOWER
4MW	165 t	20 t	300 t
8MW	450 t	35 t	650 t

Table 1. Examples of weights of main components of wind turbine. Data from: DNV-GL (2016)

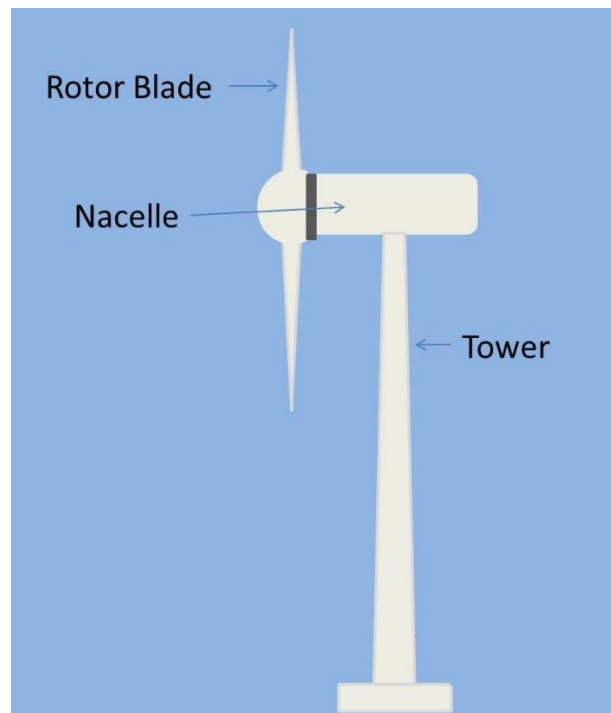


Figure 4. Main parts of wind turbine. Source: Energizect (2019)

2.2.2 Wind turbine foundations

“The primary purpose of the foundation is to provide the structural support for the wind turbine” (DNV-GL, 2016). In general terms, for offshore wind farms, we will face 6 existing structural configurations for foundations, divided into fixed and floating:

- Bottom fixed structures
 - o Monopiles
 - o Lattice or jacket structures
 - o Gravity-based structures (GBS)
 - o Tri-piles or tripods
- Floating structures

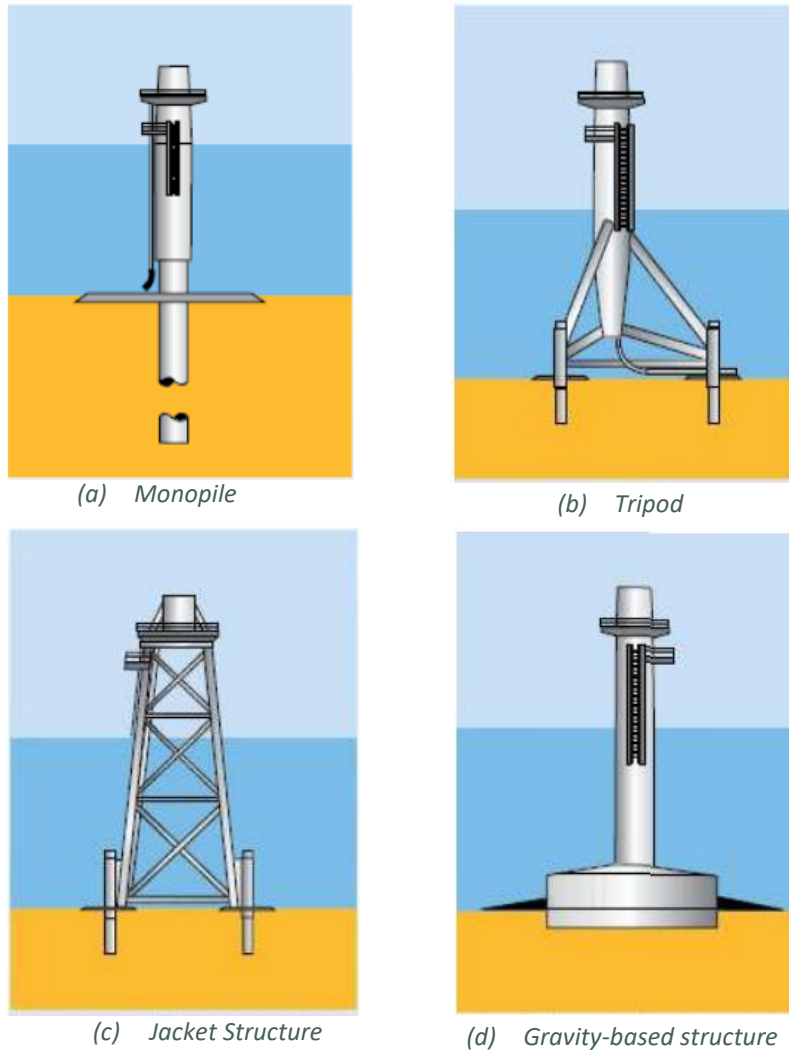


Figure 5. Types of bottom fixed foundations. Source: LHSV (2016)

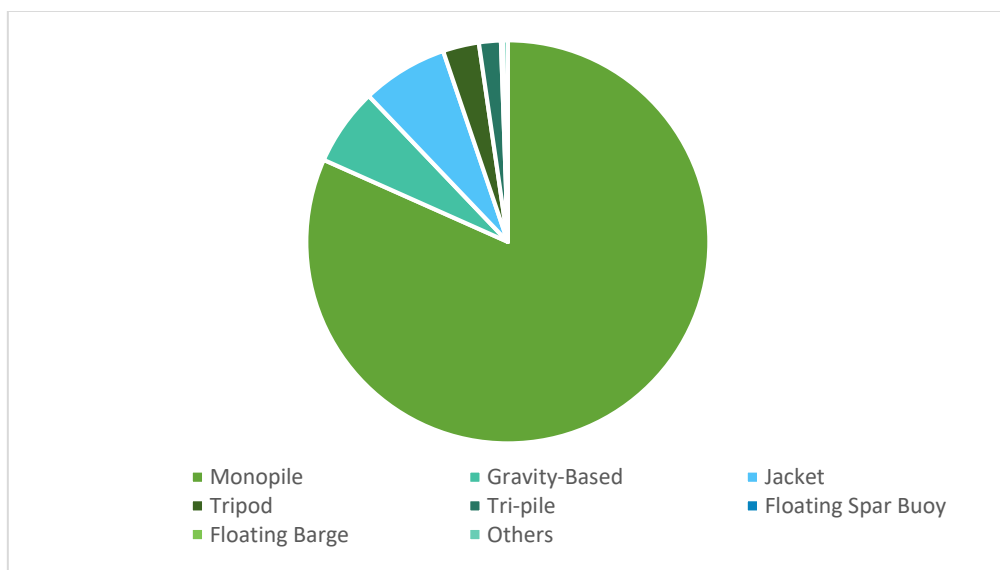


Figure 6. Cumulative Market Share - Offshore Substructures. Source: WindEurope (2018)

Type of substructure	Number of foundations	Share
Monopile	3.720	82%
Gravity-Based	283	6%
Jacket	315	7%
Tripod	132	3%
Tripile	80	2%
Floating Spar Buoy	6	0%
Floating Barge	1	0%
Others	18	0%

Table 2. Cumulative Market Share - Offshore Substructures. Data from: WindEurope (2018)

In the event of offshore fixed wind farms, the foundations range from monopiles, jackets to gravity-based structures, tri-piles and suction buckets (Figure 5). When talking about floating foundations three configurations are used: spar buoys, semi-submersibles and tension-leg platforms (TLP), seen in Figure 7.

It has been considered irrelevant talking about them or going further in this topic, which is why this section will be mainly focused on their materials and basic characteristics. Fixed structures use concrete (reinforced or not) and structural steel. Technologies for floating support structures are mainly made from structural steel. Stainless steel can be used for more protection against corrosion.

SPARS	SEMI-SUBMERSIBLES	TLP
Use predominantly widely-used and proven technology		
	Can be used in shallower waters	

Table 3. Strong points of floating structures. Data from: DNV-GL (2016)

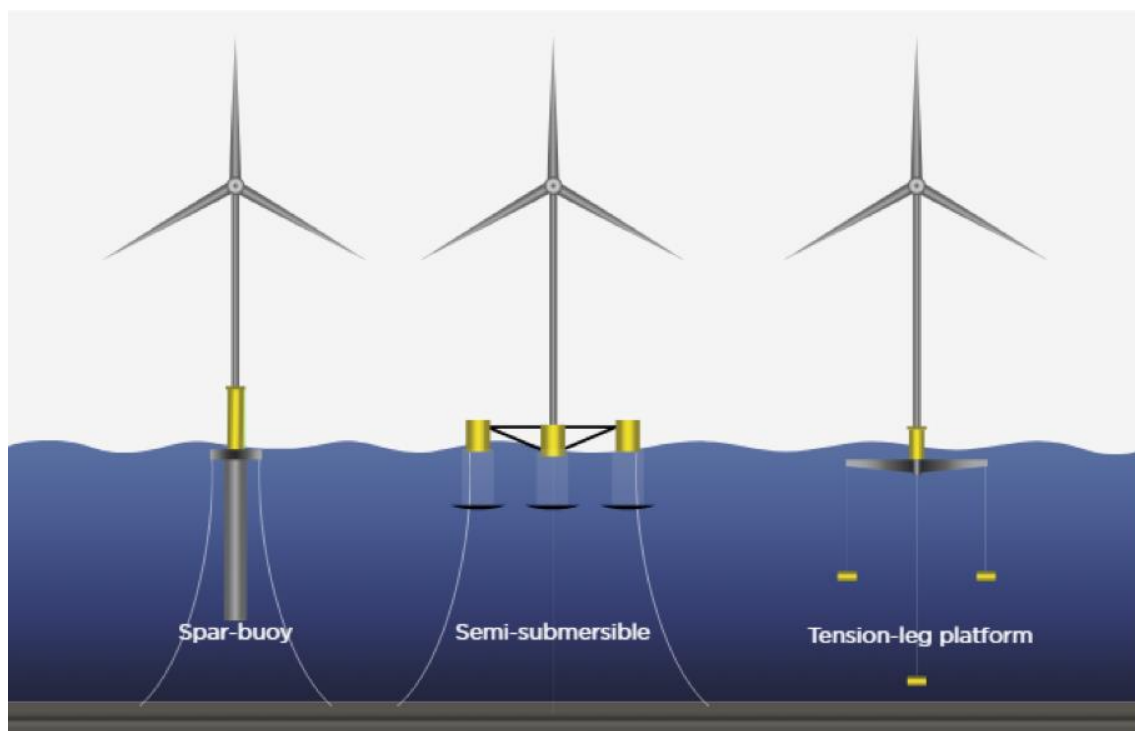


Figure 7. Types of floating foundations for offshore wind turbines. Source: AGCI (2016)

2.2.3 Offshore sub-sea cabling

The cables will carry the power between the turbines and the shore: there is no doubt that, here, cable protection is the issue of most relevance. The principal method used is simply the burial of the cables in the seabed, at depths of 1 or 2 m. Sometimes it will be required to bury them at major depths, and sometimes due to the seabed not offering enough protection or simply due to its nature, they may be impossible to bury. In these cases, other alternatives such as concrete mats or geo-fabric layers over the cable are used.

The electrical infrastructure of an offshore wind farm is formed by two cable typologies whose characteristics can be seen below.

- **Array (or inter-array) cables:**
 - Connect the turbines between them and to the offshore substations.
 - Relatively short (maximum 1-2 km).
 - Medium-voltage AC cables (approx. 33 kV).
 - Materials: XLPE insulated cables.
- **Export cables:**
 - Transmission of power from the offshore platform to the onshore station⁴.
 - Similar to inter-array cabling, but with more demanding requirements related to length and insulation.
 - Limited maximum cable length: joints will be sometimes required.
 - High voltage conductors, using mainly AC⁵ technology. If the distance from the substation to the shore is very large (50-100 km) then the use of HVDC⁶ is justified, but it entails a big increase in the dimensioning of the infrastructure. In addition, the use of HVDC requires an offshore substation to convert the AC power generated by the turbines.

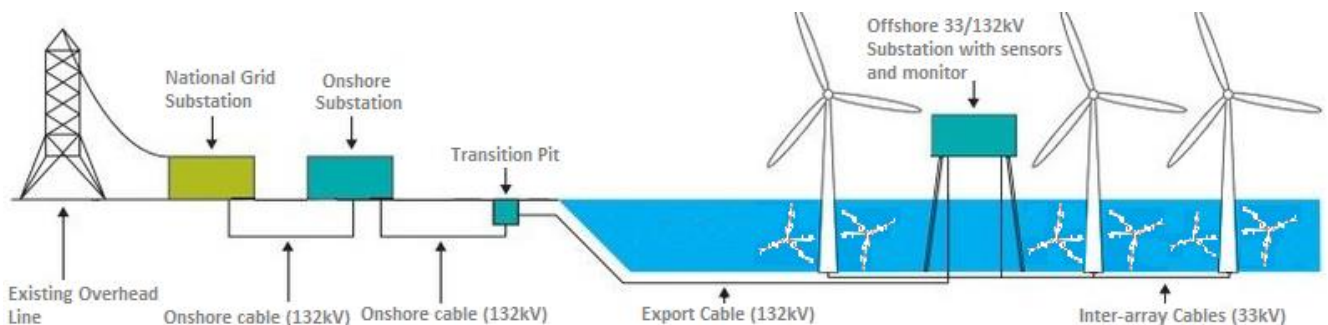


Figure 8. Example of the electrical infrastructure of a wind farm. Source: Stathclyde University (2017)

⁴ The onshore station is commissioned to carry the power to the grid.

⁵ Alternating Current.

⁶ High Voltage Direct Current.

2.2.4 Offshore substations and support structures

The existence of an intermediate substation is defined basically by the farm dimensions and its distance to shore and to the grid connection-point. Usually, the farms located more than 10 km away from shore have them.

These substations are the location for the necessary transformers for increasing the power coming from the inter array cables at approx. 30 kV up to values from 110 to 245 kV, and also the point from where the export cables will carry this power to the landfall location.

The foundations used for these substructures belong usually to the same typology as those used for the wind turbines (*Figure 5*) but since they must bear more weight, they are generally much bigger, typically employing Jacket structures.

2.2.5 Other elements

- **Onshore substations**

Designed to connect offshore installations to the onshore grid. Export cables arrive to shore and, there, they are connected to the onshore cables which through the onshore substation will be finally arriving to the grid.

- **Scour protection**

Vertical piles are likely to erode the soil around their base due to flows, mobile seabed materials and erosion induced by the waves, and eventually holes will appear (scour). Scour protection is needed to maintain enough burial and it is achieved by means of putting layers of aggregates. In shallow waters or areas with severe wave action, rock armors may be used as well.

- **Meteorological towers**

Installed to measure wind resources and climatic conditions of the project site. Usually placed on similar structures as wind turbines, but of much smaller size.

2.3 TECHNOLOGIES AND PROCESSES

Operations will mainly depend on foundation types, equipment and available vessels, distance to ports, water depths and weather conditions (Topham & McMillan, 2018). Performing the operations in the smaller possible time as well as transporting the structures as complete as possible will be sought for the sake of simplifying operations and, most important, reducing costs.

2.3.1 Stages

The whole process of decommissioning can be summarized in 3 phases:

- **Project management and planning**

Scheduling of operations and computation of time and costs, always searching for the optimal solution: the most sustainable and efficient. Revision of all obligations and requirements, development of a plan for each phase of the project and search for available vessels and equipment.

- **Removal of structures**

Turbine removal will be the first stage and is exactly the reversed installation process. After that, the foundation will be retrieved, normally by using a different vessel. Then, if existing, the substations will be dismantled and finally the cabling will be treated. After the decommissioning of all physical parts of the installation, site clearance must be carried out in the area and the surrounding area where the wind farm was placed, in order to leave the marine environment in conditions as close as possible as before the commissioning of the farm.

Monitoring of the farm will take place in all stages of the operation, pre-decommissioning and post-decommissioning.

- **Post decommissioning processes**

Inspection and cleaning of the site in regard to its recovering. Destination of retrieved materials and monitoring of any components left in place.

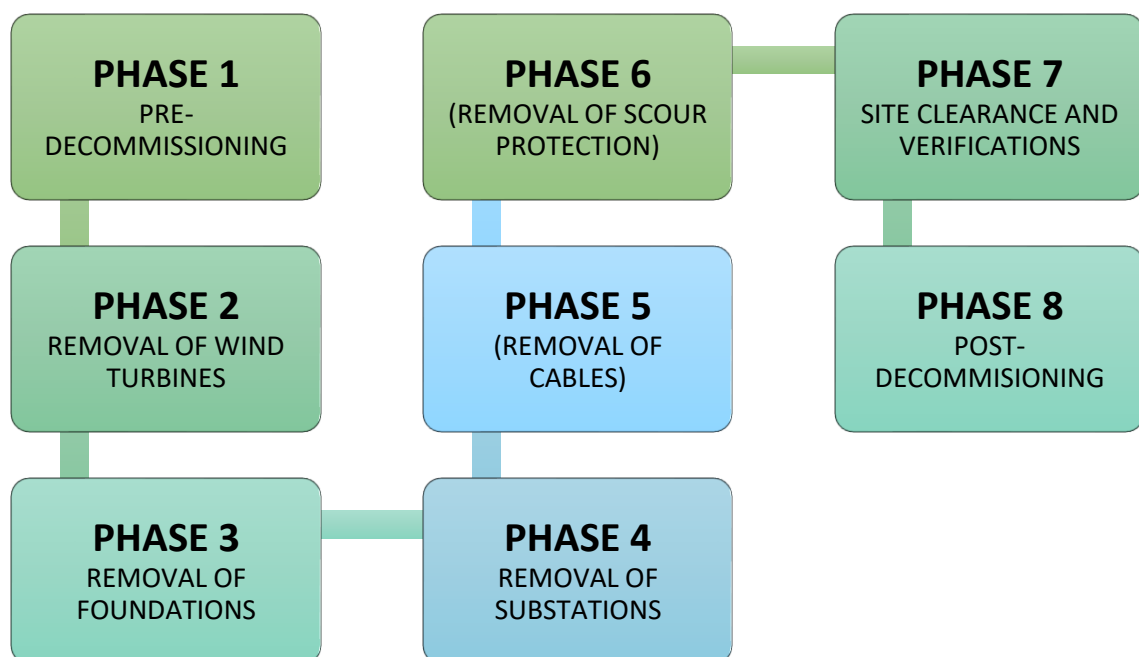


Figure 9. Decommissioning stages. Source: Own illustration.

2.3.1.1 Removal of structures

2.3.1.1.1 Pre-decommissioning

Before the removal on any part of the structure, each component, including turbines and foundations will be inspected in order to make sure its conditions are correct for undergoing the process. A final decommissioning strategy will be then developed, vessels are contracted and any necessary onshore facility is constructed.

2.3.1.1.2 Turbine removal

Turbines will be entirely removed and brought to shore to disassemble. The exact operations, as well as the vessels used, will always depend on the type of turbine and the procedures formerly used to install them in the first place. The size and weight are determinant factors for choosing the methodology of removal, which in turn will determine the size and capacity of vessels needed.

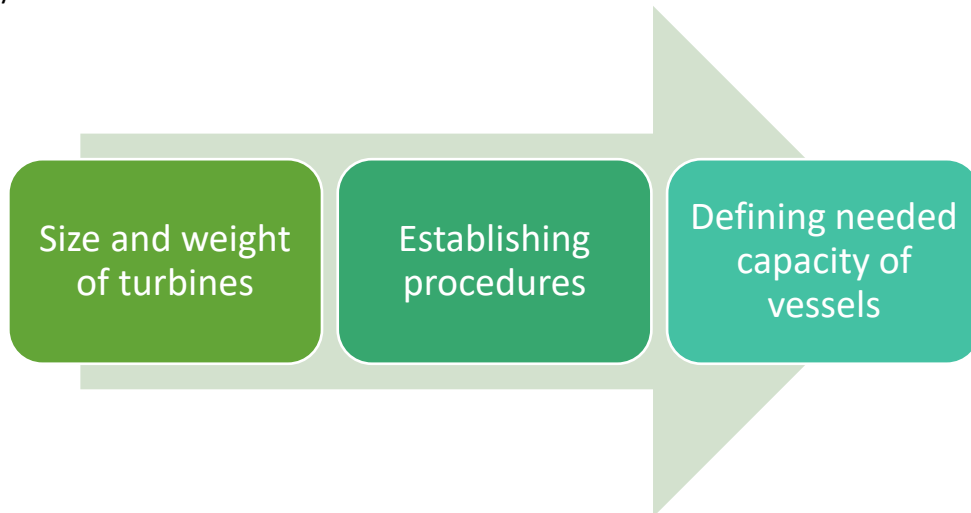


Figure 10. Decision-making in turbine removal. Source: Own illustration.

The process for removing the wind turbines is schematized below (adapted from Kaiser & Snyder):

- 1 Electrical isolation: Disconnection from grid and de-energization of wind turbine
- 2 Collection and removal of liquids/lubricants⁷ (gear and motor oils, other chemicals)
- 3 Removal of bolts and cutting of cables interconnecting components⁸
- 4 Removal of blades
- 5 Removal of towers
- 6 Lifting and transport of components to shore
- 7 Disposal

The number of lifts to remove the turbine will depend on the method used, shown on *Figure 11*.

⁷ Liquids can also be left inside the nacelle and be collected outright onshore, minimizing that way spillage risks (Topham & McMillan, 2016).

⁸ Depends on the method used, may not be always necessary.





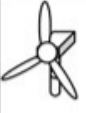





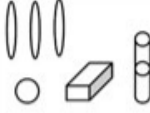
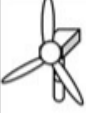


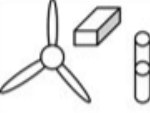
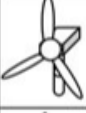



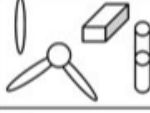



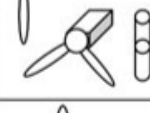
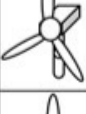
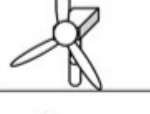


Starting turbine composed of:	Removal options (# lifts)	Step						Remove tower to give final condition
		Initial Condition	Remove blade 1	Remove blade 2	Remove blade 3	Remove hub	Remove Nacelle	
2 tower sections:  nacelle:  hub:  3 blades: 	1 (6)							
	2 (3)							
	3 (4)							
	4 (3)							
	5 (1)							
	Felling							

Figure 11. Traditional offshore turbine decommissioning options. Source: Kaiser & Snyder (2012)

The last option seen in the figure above is called and “Alternative method” and is less commonly used. The main principle is to “fell the turbine in a manner similar to cutting a tree” (Kaiser & Snyder, 2012).

- 1 Removal of fluids and hazardous material of the nacelle
- 2 Removing blades (optional)
- 3 Attaching wires to control fall
- 4 Attach flotation system
- 5 Cutting of turbine tower
- 6 Falling of turbine in a controlled manner⁹
- 7 Lift and transport to shore

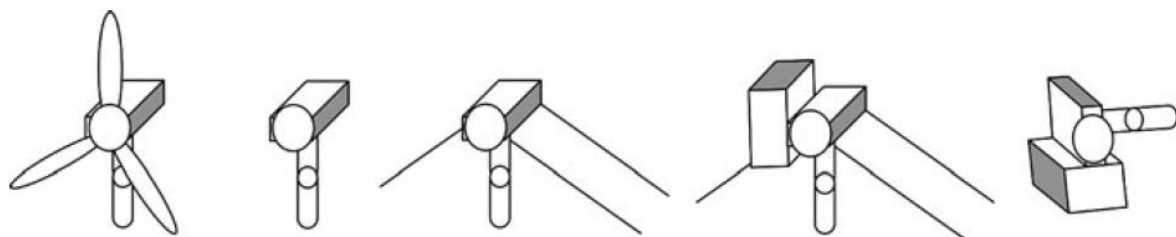


Figure 12. Alternative wind turbine removal method. Source: Kaiser & Snyder (2012)

⁹ Using methods developed for oil and gas for converting retired platforms to permitted permanent artificial reefs (Kaiser & Snyder, 2012).

This alternative method permits to cut corners, decreasing costs due to disassembly and lifts, but it increases the risks related to safety of personnel and marine life and compromises structural integrity. Also, due to the total weight of the whole structure a large crane and a large vessel would be needed, and flotation problems must be overcome.

The **procedure for dismantling floating wind turbines** is slightly different. The main difference is that turbines will be disassembled once they are returned to shore. The general process is the following:

- 1 Turbine preparation for decommissioning: removal and sealing of fluids and loose equipment
- 2 Electrical disconnection
- 3 Disconnection of mooring lines
- 4 Whole structure is towed to shore
- 5 Loosening of bolts and dismantling of the turbine¹⁰

The positive aspect of floating wind turbines is that decommissioning them is significantly less complicated than dismantling fixed offshore farms. One of the reasons that backs this up is that water depths are higher so the range of the type of vessels that can be used is wider. In shallow waters vessels are much more restricted. Other ones may be there is no need to strictly remove foundations from the seabed and that the turbine is lifted as a single piece.

2.3.1.1.3 Foundations removal

When it comes the time to remove fixed foundations, two options are possible: re-floating them or cutting them off:

1. **Removing entire foundation**
Compulsory if structure can entail a hazard to navigation
2. **Cutting foundation and leaving the rest in-situ**
It is usually the preferred option since it will be more economical to carry out and also reduces the risks to personnel. Foundations can be cut at seabed or at a certain depth below the seabed level, which is preferable as it will reduce the risk of abandoned structures becoming a hazard in the future. Landfilling of the hole left by the foundation will be sometimes necessary after the dismantling.

The removal of the entire foundation is very difficult and expensive in both monetary and time terms. Deeper excavations would be needed and that would require more expensive equipment. Also, that implies risks to personnel performing the operations and more perturbation and impacts on the marine environment. Moreover, it is assumed that the hole left by the foundation will be refilled again by natural course. If this were not to happen, re-filling operation can be done with dredged material.

¹⁰ Following the inverse process of installation. Shore-based cranes will be needed in this procedure (DNV-GL, 2016).

Dismantling processes depend on the nature of the foundation. They are schematized below for each type of structure:

Adapted from Topham & McMillan (2016), DNV-GL (2016) and Kaiser & Snyder (2012).

i. MONOPILES

- 1 Inspection of pile footings and attaching lifting points if needed
- 2 Mobilisation of vessel to site
- 3 Allow access for cutting processes by removal of scour protection if necessary
- 4 Excavation
- 5 Attachment of crane hooks to lifting points
- 6 Cutting piles below seabed
- 7 Removing of debris
- 8 Loading of foundation and shipment to shore

ii. GRAVITY BASED

It is likely that by the time the foundation has to be decommissioned a marine habitat has developed around the base of the foundation, so unless the entire removal is compulsory, usually the base of the foundation will be abandoned in place and the tubular section will be cut and removed.

- 1 Study structural integrity of foundation
- 2 Place lifting attachments if required
- 3 Removal and disposal of sediments, ballast and scour protection from around the base
- 4 Cutting of section and lifting of foundation
- 5 Loading onto vessel and transportation to shore
- 6 Inspection of seabed and removal of debris

iii. JACKET

Jacket foundations can be lifted in a single step by cutting all the legs at a reasonable depth.

- 1 Give access to cutting location by excavation and removal of seabed
- 2 Separation of bolted joints and lifting attachments
- 3 Attachment of crane
- 4 Cutting of the legs
- 5 Lift of structure, loading on vessel and transportation to shore

2.3.1.1.4 Offshore substation removal

This sub-section concerns the substation platforms that locate the transformers and also meteorological towers, using the same or a different foundation structure relative to the wind turbines.

Offshore substations are divided in two parts that will be dismantled separately: foundation and topside¹¹. The range of foundations are the same as for the wind turbines, so its dismantling will follow the procedures mentioned before.

- 1 Topsides structures are removed as single components and transported to shore¹²
 - i. Empty structure of oils and resins
 - ii. Mobilisation of lifting vessel
 - iii. Disconnection of substation from the grid and de-energisation
 - iv. Installation of lifting points and cutting connections with foundation
 - v. Lifting, loading and transportation to shore
- 2 Foundations
 - i. Monopile: cutting and removal of foundation
 - ii. Jacket: cutting of leg piles and lifting of piles and jacket together
- 3 Transport to onshore location for offloading, disposal or reefing
- 4 Recycle as scrap or landfill disposal

The decommissioning process for meteorological masts is very similar to the one performed during turbines' dismantling.

2.3.1.1.5 Cable removal

O&G¹³ pipelines are allowed to be abandoned in place if it can be proved they are not a hazard to navigation, commercial fishing, leisure activities or have any other interference with users. Regulations on cable decommissioning when it comes to renewable energy are not still clearly developed but, on the whole, one of the three following solutions is adopted:

1. **Complete removal of inter-array and export cables.**

Preferred option if the condition presented earlier is not fulfilled, if they are not deeply buried or if they are located in areas that require maintenance draining.

Removal process:

- Excavation and raise of cables
- Cutting of the required sections, as near as possible to foundations
- Attach the cable to a recovery winch
- Retrieving of cable end to drive it up onto the recovery vessel (by means of an engine)
- Returning remaining ends to seabed
- Recovery and transport (by means of an hydraulic shear)

The costs of fully removal are very similar to the costs of cable installation, asides from causing significant marine disruptions.

¹¹ Usually the heaviest component of the whole wind farm.

¹² Meteorological towers can usually be cut in half or removed as a whole, while the transformer can only be lifted whole

¹³ Oil and gas

2. Leaving in place all inter-array and export cables.

This is the case that concerns the installation most of the times. Leaving the cable in-situ involves cutting the cable at the foundation base of all turbines and burying the end to a minimum depth. If that were not possible, concrete covers can be employed. When cables are left in place, risk evaluation and monitoring is required to ensure they do not become exposed.

3. Leaving in place a portion of inter-array and export cables.

2.3.1.1.6 Other operations

- Onshore elements

After the cease of operation of the wind farm, all onshore substations must be dismantled and the grid connection building must be demolished. There is no requirement for removing the onshore cables if they are buried and prove to not be an environmental danger.

- Scour protection

In order to avoid site disturbance¹⁴, in most cases scour protection will be left in place. If it were to be removed (in situations where it is mandatory by regulations, or external cuts of the foundations are needed), that would be done by means of a mechanical dredge or crane vessel.

- Site clearance

Removing all potential debris or residues generated by the operation of the wind farm that may affect the environment or the seafloor is the last stage of decommissioning. After that, a verification will be conducted to ensure all site clearance operations have been correctly carried out.

In O&G offshore installations the area that must be cleared is specified in function of the type of structure. However, for offshore wind farms, lack of regulations is again present. That is comprehensible, though, as in O&G installations there is only one structure, but when it comes the case of wind structures, we are facing one to one hundred structures spread across the scope zone. The plainest solution would be simply to extrapolate the rules for O&G and define the radius of clearance in function of the type of structure present. Another option would be to define the clearance area in function of the area crated by all offshore facilities plus a buffer zone.

2.3.1.1.7 Material disposal

Once the materials have been transported to shore, it is time to decide whether they will be re-used, recycled or disposed. Options are displayed in *Figure 13*. Recycling will be studied in more detail later on, in *Section 3*. The priority will always be to reuse the components. If that is not possible, the following option would be disassembling the materials onshore and process them in order to recycle all the plausible materials. If none of these two options was viable, materials would be disposed in appropriate landfill.

¹⁴ Along the years, it may have become substrate for invertebrates, and as in gravity foundations, a marine habitat is likely to develop around the structure.

The simplified scheme for decision-making concerning recycling or disposal would be the following:

recycling value

$= f(\text{weight of component}, \text{cutting cost}, \text{scrap steel price}, \text{transportation cost})$

disposal cost

$= f(\text{processing cost}, \text{transportation cost}, \text{disposal fees})$

recycling cost = cost of cutting steel + cost of transportation

- If *recycling cost* > *resale value* and *recycling cost* > *cost of landfill disposal* then material will be recycled.
- If *recycling cost* > *resale value* and *recycling cost* < *cost of landfill disposal* then material will be disposed.

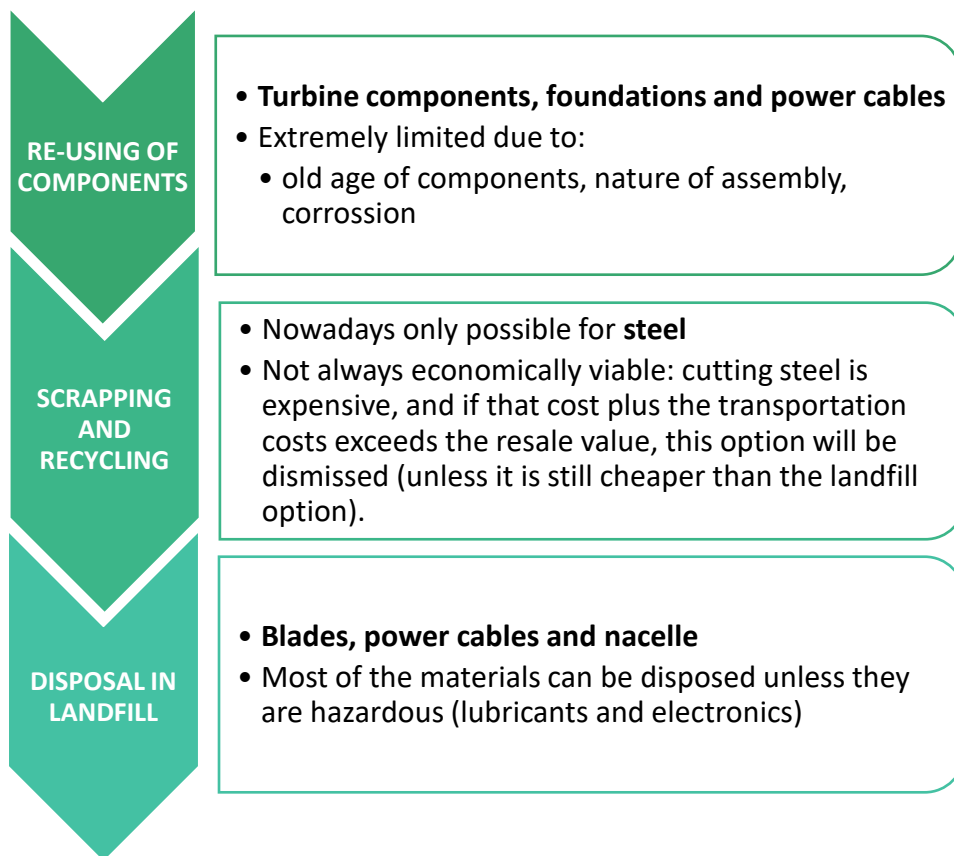


Figure 13. Summary of material disposal. Source: Own illustration.

2.3.2 Vessels and logistics

2.3.2.1 Installation vessels

Presumably the vessels used for installation will be the ones used during the decommissioning process. *Figures 14 and 15* show the type of vessels most likely to be involved in dismantling. Cable lying vessels will not be treated in this section.

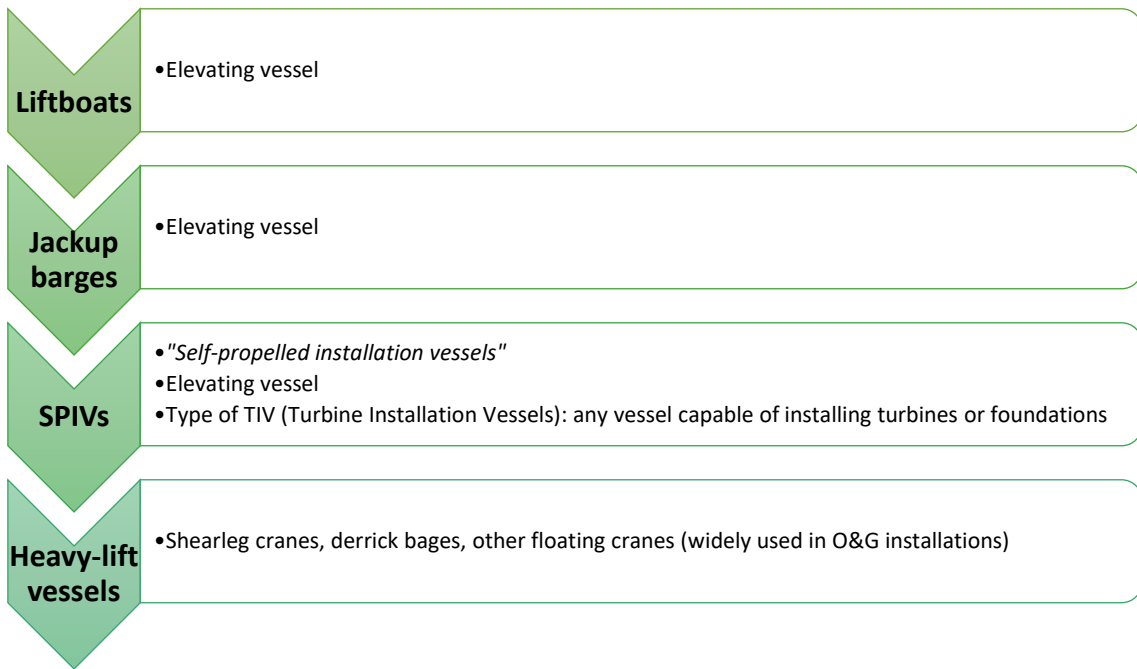


Figure 14. Main categorisation of installation vessels. Adapted from: Kaiser & Snyder (2012)



(a) Liftboat



(b) Jackup barge



(c) SPIV



(d) Heavy-lift vessel

Figure 15. Type of installation vessels. Source: Kaiser and Snyder (2012)

- **Liftboats**

Liftboats consist on self-propelled vessels with three jack-up legs that form a rigid elevated platform. They are barge-shaped and their range size is very wide, as seen in *Figure 16*. To have an order of magnitudes: Large liftboats, with crane capacities from 200 t are usually capable of carrying one or two turbines. In contrast, small liftboats are not suitable for most offshore work.

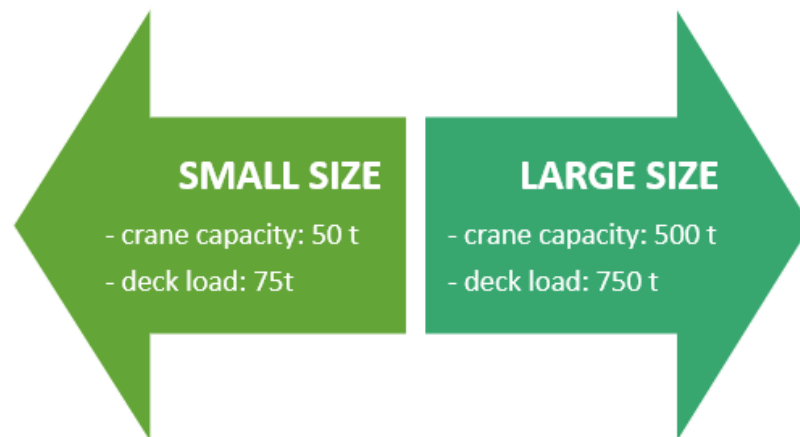


Figure 16. Range of liftboats. Source: Own illustration.

- **Jackup barges**

This kind of vessel has usually four legs. As they are not self-propelled, require a tow to site. A small jackup barge can carry two turbines and a large one may carry six to eight turbines.

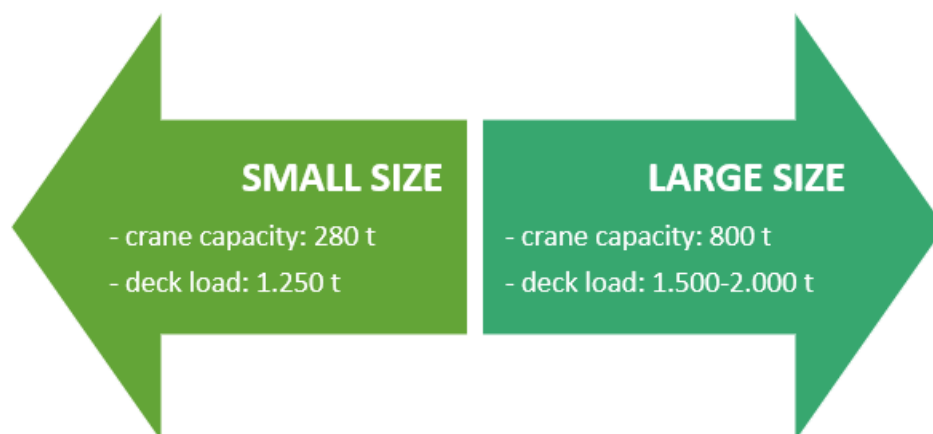


Figure 17. Range of jackup barges. Source: Own illustration.

- **SPIVs**

Consist of large vessels with four to six legs. They are self-propelled, and most of them are ship-shaped, but may also be column-stabilized or barge shaped. Main differences from both anterior cases are propulsion and size. Depending on deck loads and spacing, are generally able to carry six to eight turbines.

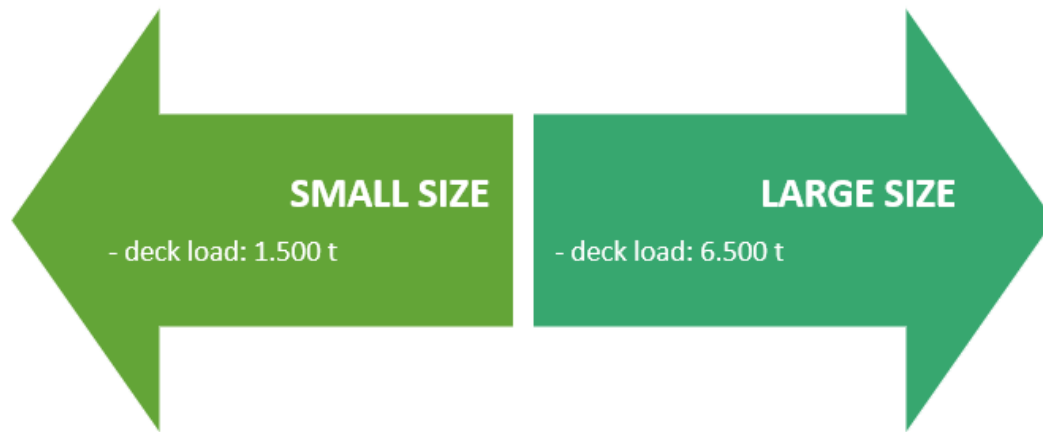


Figure 18. Range of SPIVs. Source: Own illustration.

- **Heavy-lift vessels**

Heavy-lift vessels are the largest ones nowadays found in the industry. They are equipped with high capacity cranes and can be either dynamically positioned or conventionally moored. Also, they can be self-propelled or not. They are not usually involved in the installation of turbines, but can be a support for foundations, substations or even fully-assembled turbines.

VESSEL	CHARACTERISTICS			CAPABILITIES			
	Self-propulsion	Legs	Shape	Installation activity			
				Foundation	Turbine	Cable	Substation
LIFTBOAT	Yes	3	Barge	Unlikely	Yes	No	No
JACKUP BARGE	No	4	Barge	Yes	Yes	No	Yes
SPIVs	Yes	4-6	Ship	Yes	Yes	Yes	Yes
			Barge				
			Column-stabilized				
Heavy-lift	Yes/No	---	Barge	Yes	Unlikely	No	Yes

Table 4. Summary of the main characteristics and capabilities of installation vessels.

Adapted from: Kaiser and Snyder (2012)

Vessel	Type	Operational water depth (m)	Crane capacity (t)
<i>Sea Power</i>	SPIV	24	100
<i>Sea Energy</i>	SPIV	24	100
<i>Rambiz</i>	Shearleg crane	>100	3.300
<i>Sea Jack</i>	Jackup barge	35	1.300
<i>Titan 2</i>	Liftboat	60	400
<i>Buzzard</i>	Jackup barge	45	750
<i>JB 114 and 115</i>	Jackup barge	50	280
<i>Thalif</i>	Heavy-lift vessel	>100	14.200
<i>Edge Barge 5</i>	Shearleg crane	>100	2.000
<i>Taklift 4</i>	Shearleg crane	>100	1.600
<i>Kraken and Leviathan</i>	SPIV	40	300
<i>Resolution</i>	SPIV	35	300
<i>Excalibur</i>	Jackup barge	30	220
<i>Lisa A</i>	Jackup barge	50	600
<i>MEB JB1</i>	Jackup barge	40	270
<i>Goliath</i>	Jackup barge	50	1.200
<i>Sea Worker</i>	Jackup barge	40	400

Table 5. Example of vessels used in offshore wind farm construction in Europe.

Source: Kaiser & Snyder (2012)

2.3.2.2 Support vessels

These are the secondary vessels that will provide support during the process. Several types of vessels belong to this category, such as dive support vessels, crewboats, multicats, tugs, dredging and scour vessels. Their size and composition will vary in function of the needs and size of the wind farm, and specially in function of the capacity of the main vessels.

- **Dive support vessels**

This type of vessels is conceived to offer a place to launch, supply, recover and, in general, to assist divers. Offshore dive support vessels are much smaller than those used in O&G industry¹⁵.

- **Crewboats and workboats**

They are usually 10-25 m long and able to carry 10 to 15 people. Their functionality is mainly transferring personnel and crew, but are also used for the conduction of environmental studies, support of divers in shallow waters or the enforcement of safety zones.

- **Multicats**

Usually 12-30 m long, equipped with a small crane (able to lift up to 50 t) and a large deck. Their main role is anchor handling, but they can also support other duties such as light transport, diver support, dredging, etc.

- **Tugs**

Used to tow non-propelled vessels from shore to operation zone. Normally they come with a small crane for anchor handling.

- **Dredging vessels**

They are very diverse depending on the needs, but fundamentally they consist on a backhoe excavator placed on a barge.

¹⁵ Operations take place in shallower waters, so saturation diving is not necessary.

- **Scour protection vessels**
Scour protection is usually carried out by a side dumping barge.
- **Cargo barges**
Used for the transportation of components.

2.3.2.3 *Other vessels*

- Cable laying vessels
- Mobile cranes
- Surveying vessels

2.3.2.4 *Summary of vessel and equipment selection*

Vessel selection depends of number of turbines and foundations to be removed, weights, water depths and seabed type, and obviously on the market availability (Topham & McMillan, 2016).

- Vessel requirements for wind turbines

The selection of a vessel for decommissioning wind turbines is function of the size, weight and height of turbines to be, and it highly depends on the chosen removal option. Wind turbine removal will usually mean weights from 100 to 200 t and can be performed by liftboats, jackup barges and SPIVs. Cargo barges to transport turbine components and tug in case of not using self-propelled vessels will be also needed.

- Vessel requirements for foundations

Decommissioning of foundations sometimes implies inspections, excavation and removal, and carrying weights close about 200 to 500 t.

In the pre-decommissioning part, where inspections are to be carried out, usually divers or ROVs¹⁶ will be needed. For the removal of mud and cutting processes, a simple workboat will be required and in the event of removal of ballast a suction, dredging vessels are necessary. Excavations will require dredging vessels and some other excavation equipment. Finally, for the removal of foundations, heavy lift cranes, jackup barges, SPIVs or heavy-lift vessels can be used, function of the weight and size of foundations¹⁷. As before, cargo barges (transportation vessels) for material transport and tugs for propulsion may be needed.

¹⁶ Remotely Operated Vehicles.

¹⁷ It is likely to happen that a different vessel from the one used for turbine removal performs the foundation operations.

2.3.2.5 Logistics

Logistics of all procedures are an important part and must be carefully planned. Transportation strategy depends again on the number of turbines to be decommissioned, and also on the distance to port (Topham & McMillan, 2016).

Either a self-propelled vessel is used to execute all removal operations, so the deck is filled to its total capacity and then returned to port, or a jackup performs all lifting operations and independent barges carry out the transportation procedures; so, in short, two strategies are available:

1. Multitask decommissioning vessel
2. Decommissioning vessel and independent transportation vessel

- **Workflow and logistics of wind turbines** (*from Kaiser & Snyder, 2012*)

- 1 Mobilize vessel and cargo barge to location
- 2 Prepare turbines for cut and lift operations
- 3 Remove turbine in 1-6 lifts¹⁸
- 4 Transport all components to an onshore site for reuse/recycling/disposal

- **Workflow and logistics of foundations** (*adapted from Kaiser & Snyder, 2012*)

- 1 Mobilize vessel and cargo barge to location¹⁹
- 2 Gain access to the zone where the foundation will be cut
- 3 Cut foundation
- 4 Cut cables
- 5 Remove pieces
- 6 Transport all components to an onshore site for reuse/recycling/disposal
- 7 Offload, disassemble and remove internal equipment

2.4 EXISTING CASES

As previously stated, decommissioning of floating structures has evolved from existing cases of previous dismantling of offshore gas and oil constructions and other marine structures such as bridges, ports and harbours. Over the years, these technologies have been slowly adapted to the challenges of the development of new floating wind structures.

For the sake of simplicity some real cases will be studied in this section, starting from a general overview of technical aspects of decommissioning offshore gas and oil structures and ending with an introduction to two actual real examples of offshore wind farms.

¹⁸ Foundation can be prepared for removal while the tower is being lifted (Topham & McMillan, 2016).

¹⁹ This can be done during the removal of the turbines.

2.4.1 Comparative with Gas and Oil offshore structures

When handling the technological aspects, not all stakeholders agree on which is the best solution. The most common actions in this field are the following ones:

1. Do nothing
2. Remove topsides to shore
3. Remove topsides and part of substructure
4. Remove topsides and whole structure
5. Remove topsides, whole structure and cut wells and piles to 5 meters

The scope of work is reduced to the four types of installations:

- Fixed platforms
- Moored/tethered platforms
- Pipelines
- Subsea structures

Those that are most difficult and that present the most engineering challenges are the fixed structures, and the same happens in offshore wind. The easiest structures to dismantle are the ones simply moored. The only viable option for floating structures, though, is its complete removal. Legal options for decommissioning are shown on *Table 6* below.

INSTALLATION	WATER DEPTH (m)	WEIGHT (t)	DECOMMISSIONING OPTIONS			
			COMPLETE REMOVAL	PARTIAL REMOVAL	TOPPLING	LEAVING IN PLACE
Fixed steel	<75	<4000	Yes	No	No	No
	>75	>4000	Yes	Yes	Yes	No
Fixed concrete	<75	<4000	Yes	No	No	No
	>75	>4000	Yes	Yes	Yes	Yes
Floating	<75	<4000	Yes	No	No	No
	>75	>4000	Yes	No	No	No
Column	<75	<4000	Yes	No	No	No
	>75	>4000	Yes	Yes	Yes	No
Sub-sea	<75	<4000	Yes	Yes	Yes	Yes
	>75	>4000	Yes	Yes	Yes	Yes

Table 6. Legal options for decommissioning. Source: P.A.Meenan (1998)

The technical options assessed in O&G structures for pipelines can be extrapolated to cabling:

- Remove to surface and then to shore
- Bury (by retrenching or by rock dumping)
- Partial removal
- Leave in place

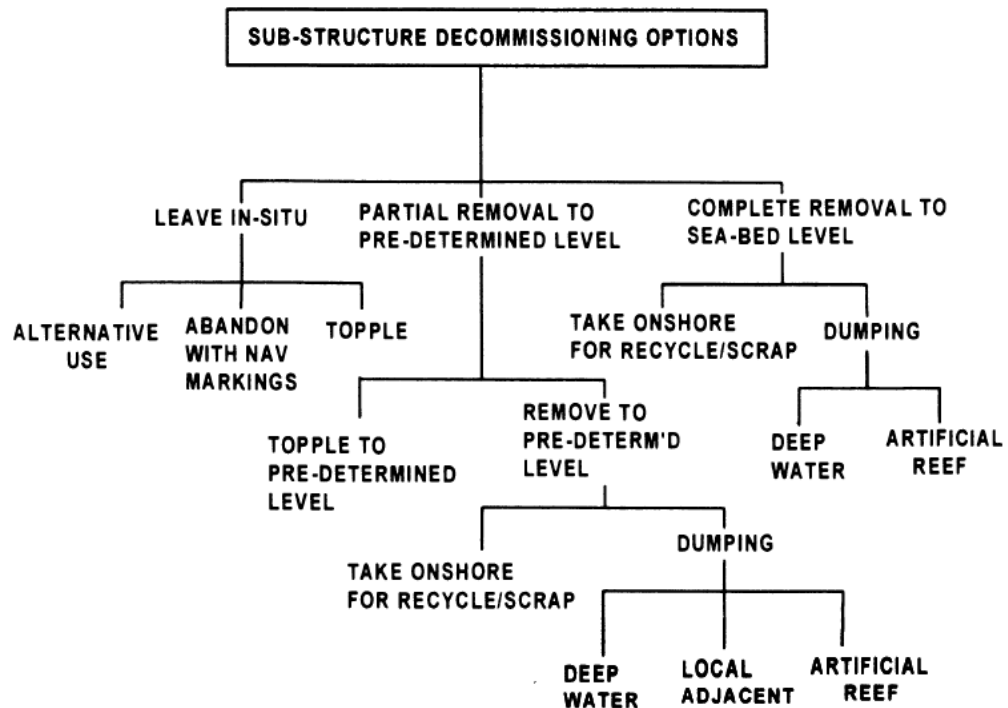


Figure 19. Decommissioning options for O&G projects. Source: P.A.Meenan (1998)

The main and basic concepts concerning O&G decommissioning are listed below (adapted from Meenan, 1998) and the main processes involved in decommissioning an O&G installation are shown on Table 7.

- Complete removal is not a problem
- The only drawback for moored structures is dock accommodation
- Original set of construction sites will be used for dismantling as is the only economically justifiable solution
- Pipelines do not require to be removed
- Modification for re-use is unlikely profitable
- Recycling and re-using of the materials is a field that needs more studies since it is very interesting to close the cycle
- Onshore dismantling option is more hazardous to safety and health than deep water disposal
- Possibility of re-use of facilities such as floating platforms

PREPARATION	Flushing and cleaning tanks
	Processing equipment
	Disposal of hydrocarbon
	Removal of loose equipment
	Strengthening of steelwork and lifting points
PLUGGING AND ABANDONMENT	Sealing the borehole
	Inserting temporary/permanent plug
REMOVAL OF TOPSIDE STRUCTURES	In pieces
	In a single lift
	Separation at the joints between platform and foundation
	Transport to shore
REMOVAL OF FOUNDATION	In pieces or in a single lift
	Cutting of piles underwater (2-5m below seabed level)
	Concrete foundations: de-ballasted and floated or lifted or cut underwater to sections that can be handled
	Transport to shore
DECOMMISSIONING OF PIPELINES, CABLES AND SEABED STRUCTURES	Usually left in-situ
SITE CLEARANCE	Removal of debris and loose materials
ONSHORE DISMANTLING, DISPOSAL AND RECYCLING	Carried out in specialized facilities

Table 7. Main processes of decommissioning O&G installations. Adapted from: DNV-GL (2016)

	Offshore wind	O&G
Water depth	10-50 m	Hundreds of meters
Distance to shore	Less than 100km	Hundreds of kilometers
	Practically identical installations	Single complex entities
Weight	750 t (6MW turbine model)	≥10.000 t (topside of an oil platform)
Loads	Subjected to high and fluctuating overturning forces	Subjected mainly to dead-load weight
Pollution	Clean	Contaminated by hydrocarbon residues
Explosion potential	No	Yes

Table 8. Main differences between O&G and offshore wind structures. Adapted from DNV-GL (2016)

Table 8 above shows the **main differences** between O&G offshore installations and offshore wind farms, but they also share some **similarities**:

- Operation in open sea
- Similar range of support structures employed (even though they have different dimensions)
- Similar range of vessels used
- Techniques used for corrosion protection
- As oil and gas companies, energy companies are obligated to remove all structures and to clear the site where they were operating
- Pipelines and cables can be abandoned in situ
- Partial removal of floating structures is not allowed

As there is a lot of experience in the O&G decommissioning field, nowadays the procedure involves relatively low technology: standard equipment and standard procedures are established. The same situation is expected in the offshore wind area in some years, but for now the operations are estimated to need much more time and space. This, along with the highly dependence of actions on weather conditions, makes offshore planning much more challenging. Some of the breakthroughs that made possible going from the decommissioning of oil and gas to dismantling offshore farms were the developments in the cutting techniques, allowing the cutting under water of big steel wires and huge concrete structures. Also, the appearance of ROVs for inspection and surveillance was a huge impact in terms of safety.

2.4.2 Vindeby

The floating offshore wind farm in Vindeby (Denmark) was the first offshore farm ever built and therefore the one of the firsts to be dismantled to this day. It was commissioned in September 1991 and its dismantling started in March 2017, after 26 years of life. This fixed offshore farm was formed by 11 turbines, placed 1.5-3 km from the shore and a total export capacity of 5MW. The foundation type was gravity-based (*Figure 5.d*) for water depths from 2 to 7 meters.

The process is shown on Table 9 below.

PART	PROCESS/OPERATION	EQUIPMENT/VESSELS
BLADES	Dismantled and taken down individually	Mobile crane Jack-up vessel
NACELLE		
TOWERS		
CONCRETE FOUNDATIONS	Broken down on site and collected	Hydraulic demolition shears Hydraulic hammer Milling tools
REINFORCEMENT STRUCTURES		

Table 9. Decommissioning process of Vindeby. Source: Vindeby decommissioning plan (2017)

The components of the wind turbine and part of the foundations were shipped to Nyborg Port for its recycling and they were used for other wind turbines. Blades were expected to be reused for research on noise barrier concept.

2.4.3 Kincardine

Kincardine is the first case on an offshore floating farm ever built. Its construction started in March 2018 and it is expected to last 2 years, being fully commissioned in June 2020. According to its decommissioning program the design life of the project is 25 years, so the decommissioning of the wind farm is planned for 2043 and is expected to last 9 months. The process chosen is based on the *reverse installation method*, which means simply reversing the procedure of commissioning.

PROCESS	OPERATION	VESSEL TYPES TO BE USED
1	Remove all floating units from site and return to port	Tow vessels
		Anchor handling tug vessel
2	Recover all mooring lines and anchor to port.	Anchor handling vessel
3	Recover all inter-array cables to ship and any additional marine deposits laid on the seabed (including concrete mats).	Cable laying vessel / Supply vessel with ROV
4	Cut, disconnect and retrieve dynamic cable ends of export cables	Cable laying vessel / Supply vessel with ROV
5	Rock dumping or burying the end sections of the export cable.	Rock dumping vessel or cable laying vessel

Table 10. Decommissioning process of Kincardine. Source: KOWL (2018)

It must be taken into account that this is an indicative program, so needles to assure, this initial program will undergo further modifications as the project makes progress and more studies are carried out. For example, repowering and the subject of leaving or not the cables buried in the seabed will be considered, even though it has been proved that it does not have a significative negative impact on the marine environment. Also, full decommissioning schedules must be established prior to decommissioning, for now, *Table 11* shows the indicative programming.

	April	May	June	July	August	Sept.
Disconnect machine and tow to port						
Recover all mooring lines and anchors						
Recover all inter-array cables						
Retrieve dynamic cable ends of export cables						
Burying the end sections of export cables						

Table 11. Indicative schedule for Kincardine decommissioning. Source: KOWL (2018)

Related to seabed clearance, once the dismantling is complete surveys will be performed within a radius of 200 m of each removed structure. Cables, mooring lines and anchor locations will also be monitored. If export cables become eventually unburied, they will be covered by rock dumping or concrete mattresses.

2.5 LIFETIME EXTENSION AND RE-POWERING

In the previous sections some processes and technologies in order to achieve the complete dismantling of an offshore wind farm were seen, but that is not the only solution at the end of the lifetime, there are two other options that are usually considered before the complete decommissioning. Either way, the lifecycle of a wind farm is strictly determined by the service life of the turbines and the foundations, both designed for fatigue, since, for example, some cables are expected to be able to last up to 40 years and transformers can serve for 35 years (Bulder & van Roermund, 2016).

Life-time extension means “operating the wind farm for a longer time than it was economically designed for” (Bulder & van Roermund, 2016) and **re-powering** “can be considered as a type of decommissioning” (Topham & McMillan, 2016) achieved through re-use of components. Two options when talking of re-powering are available: the replacement of minor components, such as rotors or blades (called *refurbishment*), or full repowering, which implies the whole replacement of old turbines for new, more modern ones.

As a matter of principle, the one and the other are taken into account before dismantling the whole infrastructure, but if the costs of extending the life of the wind farm extend by far the benefits, both alternatives will be straight dismissed. Life extension of a wind farm implies over-dimensioning it, which in turn implies an increase of the costs and, as stated before, to this day there is no existent regulations on which organism (authorities, government, building contractor...) shall assume that cost, so the issue remains behind a curtain.

When the extension of the operating of a wind farm is put on the table, it is necessary to know not only the conditions of the farm at that time but also the circumstances under which it has been working so far. That emphasizes again the fact that the installation must be continuously monitored to be able to carry fatigue studies.

So, from this perspective many options are set:

- i) Lifetime extension meaning only the continuity of operation without any expenses to extend the life. Some turbines may not work, but the farm would continue to provide (more limited) power.
- ii) Investing at certain components who have reached their design end of life to boost the existing assets for continued operation.
- iii) Dismantle partially the farm and place new parts or turbines²⁰.

2.5.1 Lifetime extension

It may seem odd to say that nowadays *the technical lifetime of a wind farm exceeds its economic lifetime*, but this is the point at which we find ourselves. The finance plans and subsidy schemes that support these infrastructures last, in general, 15 years. So, it is fair to say that the end of the subsidy scheme, only 15 years away from installation, is a crucial point in the life of the farm, because from that moment the value of the generated power depends only on the market value (Bulder & van Roermund, 2016). Also, from that moment, costs of operation and maintenance are expected to raise significantly, due to most of the components requiring

²⁰ This is the main principle of re-powering.

meaningful maintenance or even replacement, taking as well into account that in the future it will not be always possible to find spare parts.

Ultimately these infrastructures are reduced to the management of a usual business case based on the technical conditions of the assets and the financial proposition. To know if the continued operation of a farms makes sense, it is necessary to study that final economical backing point: after 15-16 years, the CAPEX²¹ takes a value approaching zero, which in turn implies that the energy cost becomes only a function of the OPEX²². When the OPEX is bigger than the expected incomes for the generated electricity, there is no incentive to keep the farm operating. If, by cons, it is economically feasible for the farm to operate longer, it will require a renovation of the permits that allow its performance.

Having said that, it is important to know that economic aspects are not the only ones that must be fulfilled in order to be able to operate an offshore infrastructure beyond its lifetime. It is essential to prove the safe operation by means of a certificate expended from an accredited body, as well as the renewal of the permits mentioned earlier.

In brief, the potential extension of the lifetime must be taken into account in the project from minute zero.

Hereunder, life extension will be dealt separately in regard to each wind farm component:

Lifetime of electrical infrastructure:

As stated before, protection of the cable is achieved by burying them at least 2 meters below the surface of sediment. Commonly, as export cables do not present inconveniences, the major challenge lies in the lifetime of intra-array cable system. There are three main options in order to extend the life of this cabling (Bulder & van Roermund, 2016):

- Optimization of power capacity
- Assessment condition of components
- Prevention of thermal overloading²³

But anyway, in general terms, costs of the electrical infrastructure are only determined by the installation and the burial.

Lifetime of support structures

Support structures can last around 25 years in fatigue. Their lifetime is basically determined by their design and protection to corrosion, type of foundation and loads that receive.

There are plenty of options for extending it, but the most effective would be over-dimensioning the structure, for example, by increasing the thickness of the walls, in such a way that its stiffness would also increase; making the structure more fatigue-resistant. Improving the resistance to corrosion of the substructure and an intensification of preventive maintenance are also necessary, and that is nothing but another illustration for the need for continuous monitoring.

²¹ *Capital Expense*: profit-creating capital investments.

²² *Operating Expense*: permanent cost due to the operation of a business or system.

²³ In order to avoid that, is important to carry tests and to put thermal restrictions

2.5.2 Re-powering

Re-powering of a wind farm consists on the re-use of the electrical infrastructure and foundations and replacing the wind turbines by new modern ones under two conditions (Bulder & van Roermund, 2016):

1. Turbines do not generate more power than rated power of the old wind farm
2. Loads of the support structure should not be higher than the support can carry

Re-powering of the electrical infrastructure

It must be considered from the beginning of the project so the cables can be dimensioned according to this solution, to avoid the problems mentioned earlier.

Re-powering of the support structures

To begin with, it should be clarified that current wind farm installations are not designed and/or installed for re-powering. It is expected that in 15 years, when the question of re-powering arises, as turbine technology is expected to be widely improved, the wind farm layouts and foundation technologies will be obsolete: foundations would be too small and too close to each other for modern turbines. If that is the case, it is obvious that the additional cost of over-dimensioning the structures in pursuit of re-powering or having to replace them would make no sense; that is why it is considered that innovations should move towards the adaptation of these modern future turbines to the existing foundations, which can or cannot be possible.

Regardless, if monitoring of current structures shows that the health of the structures in the future is found within acceptable values, the possibility of re-powering up to 35 years is not completely dismissed. In fact, it could be very profitable as long as similar turbines and spare parts are reachable. From the maintenance point of view, this is very attractive because that would imply using brand new technologies requiring low maintenance.

In fact, the case of first offshore repowering already occurred in **Böckstigen** (Sweden). This small-scale farm was commissioned in 1998, is located only 4 km away from shore and consists of 5 turbines. In November 2018, after 20 years of operation, the partial repowering of the farm took place: blades, nacelles and control-systems were replaced while it was possible to reuse the turbine towers, foundations and cables. It is expected that repowering will extend the life of the farm at least for 15 more years. Operations were performed in less than a year and had a cost of 5,6M€. Clearly, this example opens up a whole new dimension in the understanding of recycling and cost-saving, and leads the way to future re-powering, by proving that it is actually achievable.

On the other hand, an example of dismissed re-powering of a farm would be **Vattenfall**, (Sweden) whose operation already reached to an end (decommissioned only after 5 years of life). The decision to not replace the turbines with new ones was made on technical and economical issues: the difficulty to acquire spare parts and the huge cost of upgrading turbines and gearboxes.

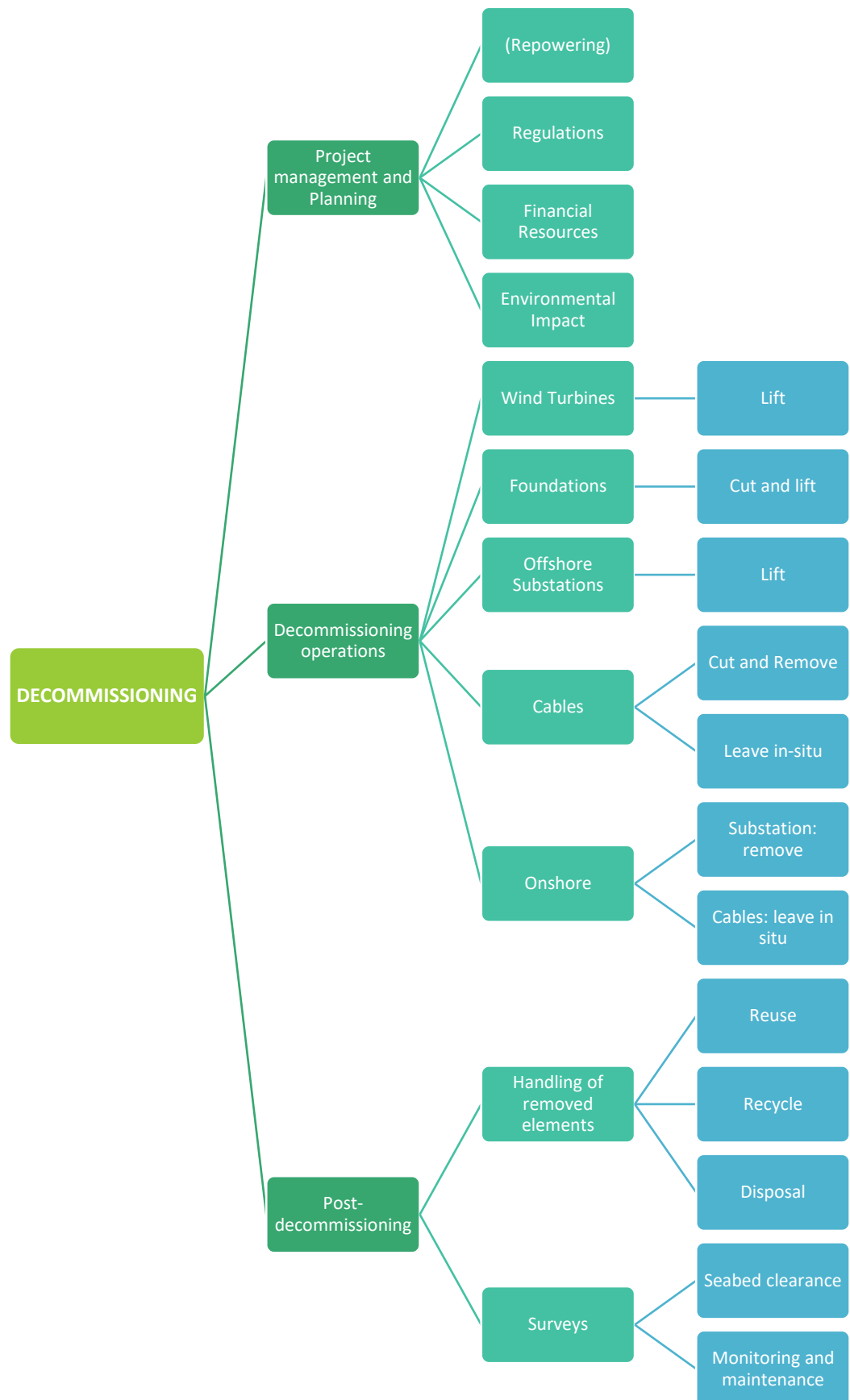


Figure 20. Decommissioning process summary. Source: Topham & McMillan (2016).

2.6 DECOMMISSIONING PROGRAMS

The decommissioning programs are the key to the planification of the process. They include the description of all operations to be executed, the technologies and vessels needed, material disposal, scheduling ²⁴ and a detailed description of all the elements to be decommissioned. Environmental, legal, and financial aspects are also reflected, as well as the guidelines on which the program is based. They should be issued at the beginning of the construction phase and reviewed through time to make modifications and adjust the points that are not established from the first edition.

There are software management tools such as *ODIN-Wind* that help in the pre-decommissioning process definition. *Figure 21* below is an example.

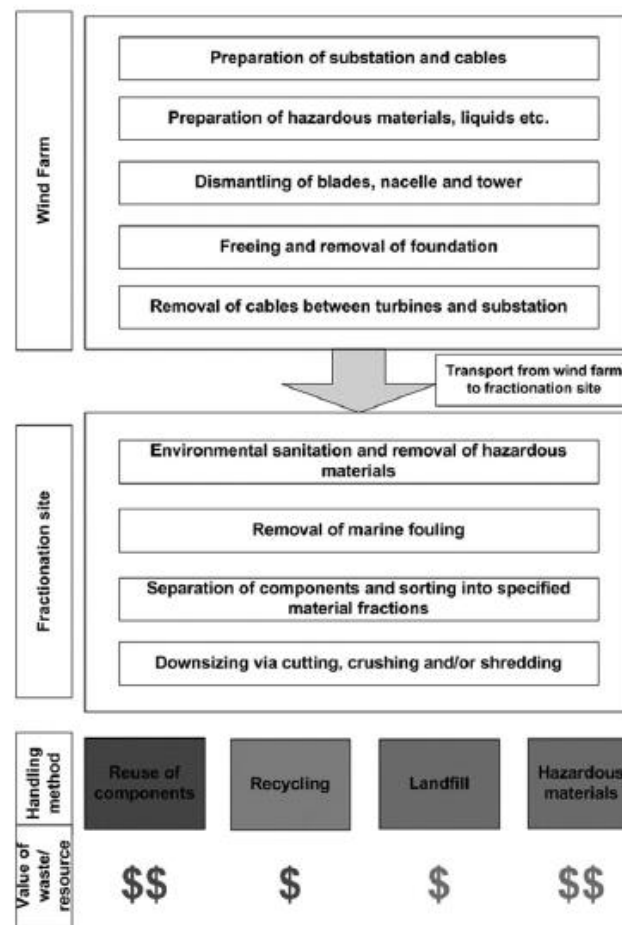


Figure 21. Decommissioning process for offshore wind turbines. Source: ODIN-WIND (2014)

²⁴ Will be subjected to vessel availability and weather conditions, therefore is not easy to plan from the very start.

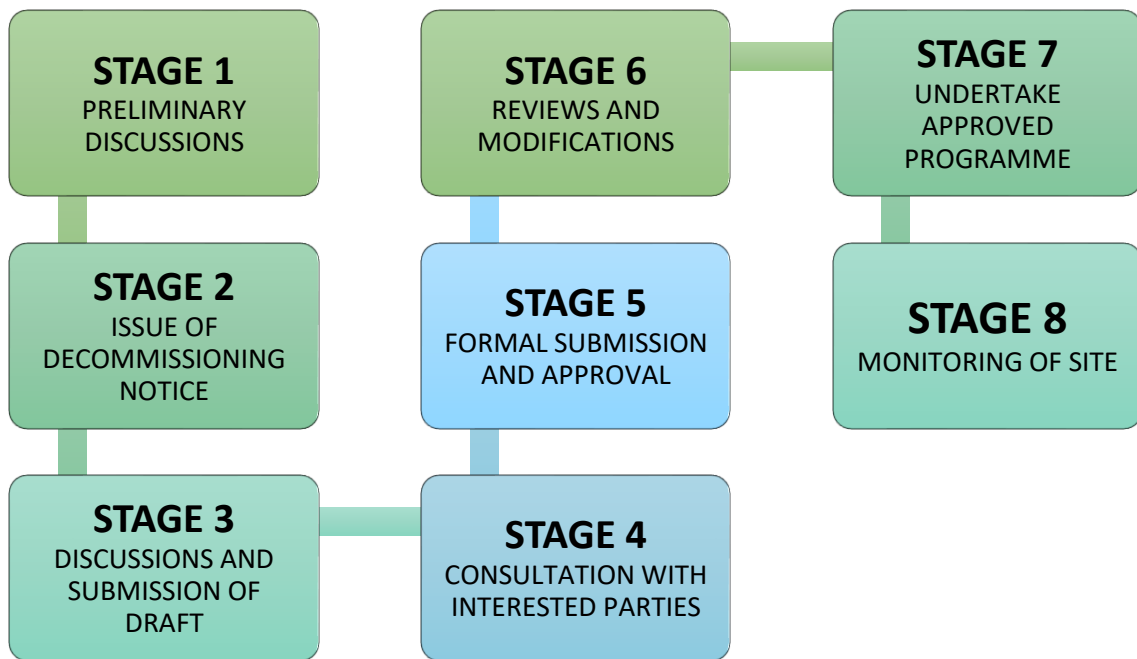


Figure 22. Process for submission, approval and review of decommissioning programmes. Adapted from DECC (2010)

Content of decommissioning programs (recommendation)

Model framework set by DECC²⁵ (2010).

1. Introduction
2. Executive summary
3. Background information
4. Description of items to be decommissioned
5. Description of proposed decommissioning measures
6. Environmental impact assessment
7. Consultations with interested parties
8. Costs
9. Financial security
10. Schedule
11. Project management and verification
12. Sea-bed clearance
13. Restoration of the site
14. Post-decommissioning monitoring, maintenance and management of the site
15. Supporting studies

²⁵ Department of Energy and Climate Change (UK).

Specifications		Gunfleet Sands	Thanet	Lincs	Ormonde	Sheringham Shoal	Greater Gabbard	Gwynt y Môr
Commission year		2010	2010	2012	2012	2012	2013	2014
Capacity (MW)		172,8	300	270	150	316,8	504	576
Distance (km)		8,5	11,3	8	9,5	17-23	26	15-13
Depth (m)		2-15	20-25	8-18	17-22	15-23	20-32	12-34
Turbines	Number	48	100	75	30	88	140	160
	Capacity (MW)	3,6	3	3,6	5	3,6	3,6	3,6
	Weight (t)	475	396	435	661	475	475	475
Expected life (years)		20	20	20	ND	20	25	20-23
Foundation	Type	Steel monopile	Steel monopile	Steel monopile	Steel jacket	Steel monopile	Steel monopile	Steel monopile
	Weight (t)	225-423	ND	225-320	250	370-500	660	200-700
	Operation	Cut	Cut	Cut	Lift + Cut	Cut	Cut	Cut
Offshore substation	Topside weight (t)	1.315,41	1.460,82	2.250,97	900,54	875	500,85	1.000-1.415,40
Scour material		Left in situ	ND	Left in situ	ND	Left in situ	Left in situ	Left in situ
Inter-array Cables	Material	Cooper	Cooper	Cooper	Cooper	Cooper	Cooper	ND
	Voltage (kV)	33	33	33	33	36	33	33
	Burial depth (m)	ND	1-2	ND	0,6	ND	1-1,5	ND
	Operation	Left	Left	Left	Left	Left	Left	Left
Export cables	Material	Cooper	Cooper	Cooper	Cooper	Cooper	Cooper	ND
	Voltage (kV)	132	132	132	132	145	132	132
	Burial depth (m)	2	1-2	1-3	2	1	1-1,5	0,5-1
	Operation	Left	Left	Left	Left	Left	Left	Left
Decommission time (days)		100	270	1.339	570	1.350	260	730
Costs (€/MW)		ND	45.308	114.629	ND	36.133	ND	125.730
Costs (€/turbine)		ND	135.924	412.665	ND	130.079	ND	452.628
Total cost (M€)		ND	13,6	30,9	ND	11,4	ND	72,4

Table 12. Summary of the decommissioning programmes available. Adapted from: Topham & McMillan (2016)

3 ENVIRONMENTAL ASPECTS

The treatment of all dismantled components is a very important stage in the whole dismantling process, given the amount of material “waste” that will be generated once the farm has been removed. The ideal output would be to be capable of re-using most of the components for other wind farms, but this particular situation is unlikely to happen as some parts may be damaged or far too much fatigued to be re-used again safely; and in the other hand, the components that could work over their lifetime are usually left in situ (e.g. cables). However, considering the re-use should always be the first option before recycling and disposal, with disposal being the last preferred alternative, only chosen if the two previous are not conceivable by any means.

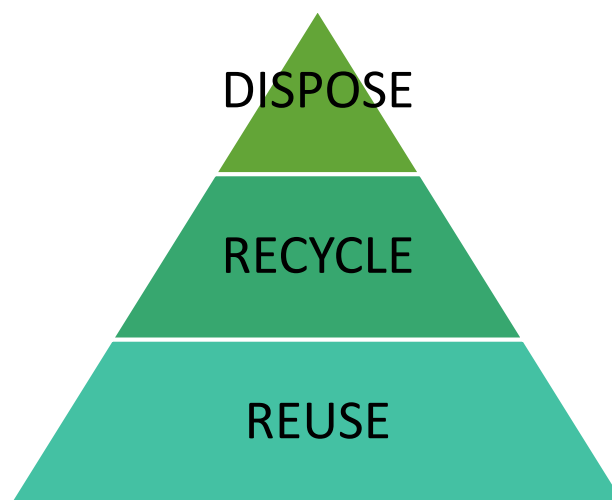


Figure 23. Hierarchy of operations. Source: Own illustration.

Furthermore, wind farms are constituted by a large variety of different materials, some of which can be difficult to recycle, either due to its nature or to high processing costs, or even to its hazardousness. *Table 13* shows the range of materials and proportion for an example of a 60MW wind turbine.

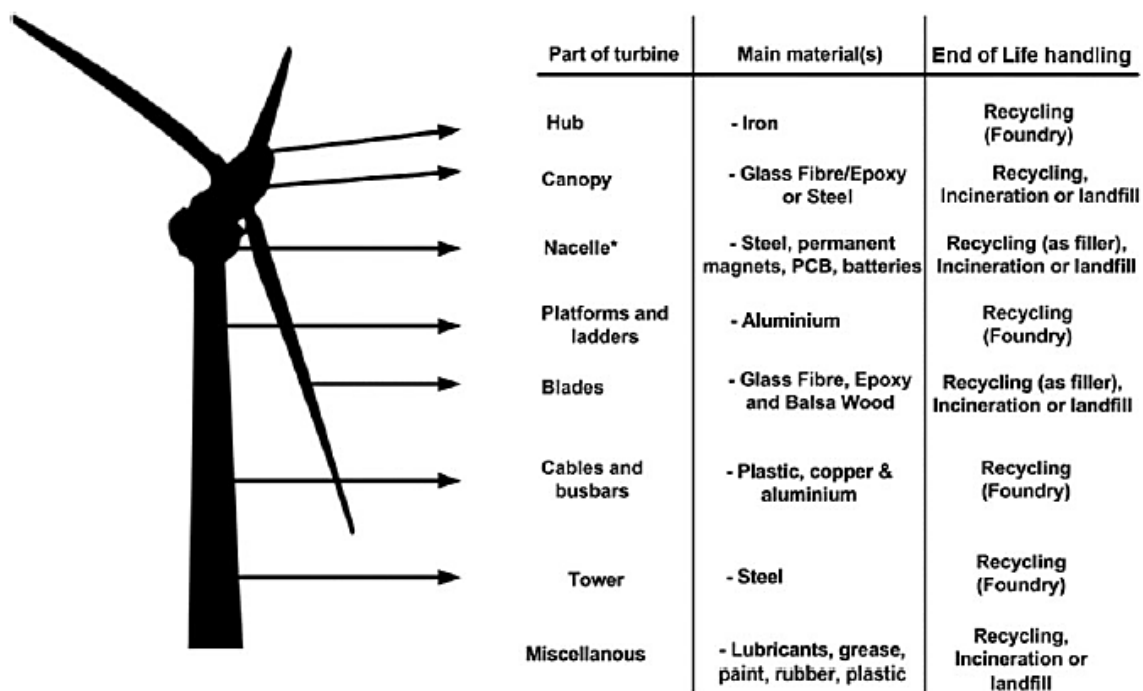


Figure 24. Turbine parts, main materials and potential disposal methods. Source: Jensen (2018)

MATERIALS USED	APPROXIMATE MATERIAL QUANTITY (kg)
Ferrous metal	6.560.000
Aluminum	104.000
Composite materials	660.000
Lubricating oil	30.000
Electronics	124.000
Batteries	36.000
Fluorescent lamps	3.800
NdFeB magnet	40.000
Copper	292.000
Balsa wood	29.000
Polyethylene	32.000
Polypropylene	6.600
Polyvinylchloride	6.000
Miscellaneous (<1%)	---
TOTAL	7.923.400

Table 13. Total potential recyclable materials of a 60MW wind turbine. Source: Jensen (2018)

From this data, it is clear that the two main materials are steel, found in almost all parts of wind turbines and foundations, and composite materials composing the blades; in approximate percentages of 83% and 8%, respectively. When comparing these materials is evident that the industry is rather much more habituated to recycling one of them: “steel is the most common recycled metal” (Jensen, 2018), which can be reused several times without significant loss of properties and which has a strong market backing steel recirculation; making this way tower, generators and gears sufficient easy to process.

For their part, material composites found in the nacelle and blades will be a little more difficult to recycle. The three solutions offered for treating them are recycling, landfill and incineration, being incineration the most common. Recycling composite materials implies not only lack of experience in the field and lack of market for the recirculated materials, but significant loss of quality and properties of the material is foreseen. Even so, some technologies for recycling them are available: that can be achieved by pyrolysis, oxidation, mechanical or chemical procedures. What they all have in common is that the final objective is to tear apart the resins from the fibers. On the other hand, if blades are incinerated, some energy recovery is expected and at the end of the procedure the ashes can be used as filler material for construction, when permitted.

In general terms, it is of great importance to take care of the potentially dangerous materials or pollutants that may be present in the wind turbine, making sure any liquid elements, such as oils, gas and other chemicals are controlled during the whole process and that they are correctly treated in specialized plants; whether they are retrieved during the early stages of decommissioning offshore or once the turbine has reached the port. Landfilling should be the last preferred option for all materials given that it is banned in some countries.

In terms of foundations, some of the concrete structures can be used to build artificial reefs if there are enough of them to achieve structural stability and complexity.

The recycling of materials is not mandatory issue yet, but it is really interesting in terms of reducing the carbon footprint of wind farms: not only CO₂ emissions are reduced by recycling but also a lot of energy is saved. Studies endorse that wind turbines can be recycled in an 80-90% of its totality (Jensen, 2018). The rate of recyclability of materials will depend on the costs derived from processing the materials and the easiness of disassembling and separating them. *Table 14* below shows the possibilities of disposal for each component and *Figures 25* and *26* schematize the most common routes.

COMPONENT	REEF	LANDFILL	SCRAP	LEFT IN PLACE
Turbine blades	No	Yes	No	No
Turbine nacelle	No	Yes	Yes	No
Turbine tower	No	Unlikely	Yes	No
Monopile-transition piece	Yes	Yes	Yes	No
Monopile	Yes	Unlikely	Yes	No
Cables	No	Yes	No	Yes
Scour protection	No	Unlikely	Yes	Yes
Substation foundation	Yes	Unlikely	Yes	No
Substation topsides	No	Yes	No	No

Table 14. Disposal options by component. Source: Kaiser & Snyder (2012)

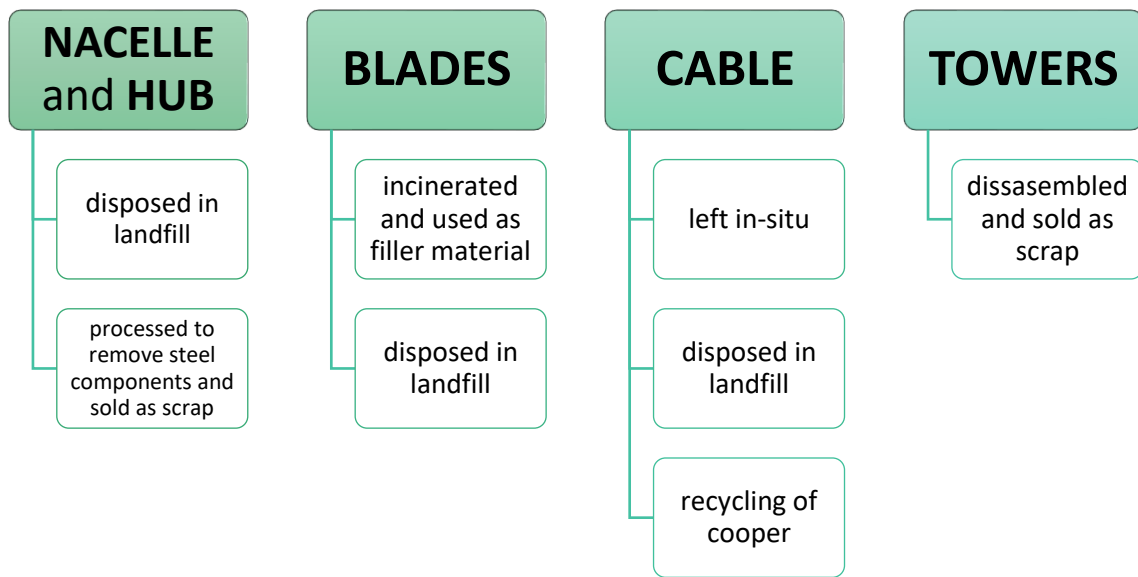


Figure 25. Most common routes for wind turbine materials. Source: Own illustration.

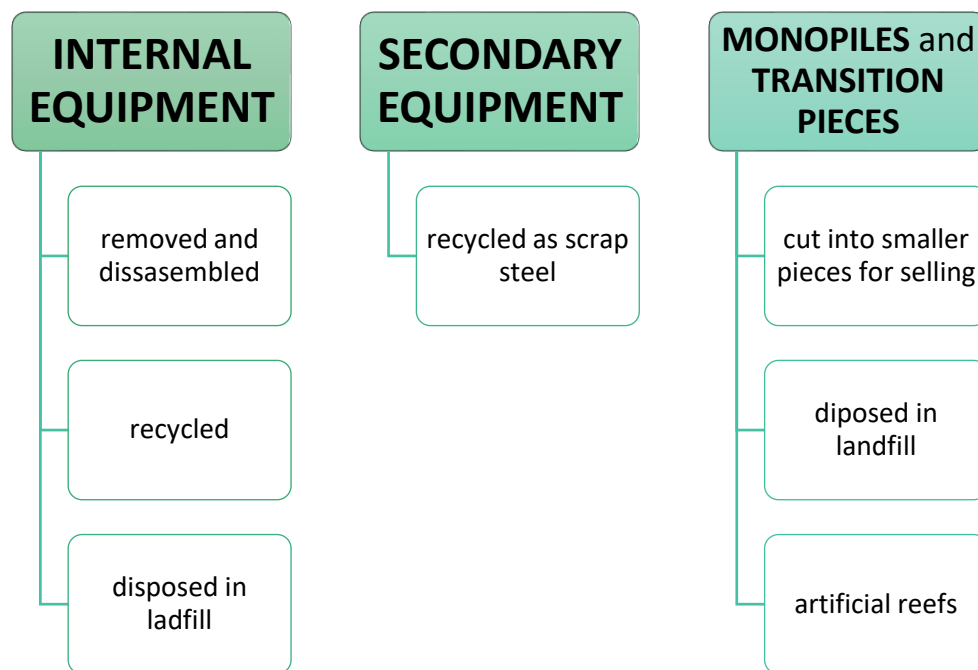


Figure 26. Most common routes for foundations materials. Source: Own illustration.

4 LEGAL AND POLITICAL ASPECTS

Given that at present no specific guidelines are yet available and day the UK is one of the countries with more offshore wind experience, a summary of the principal points and recommendations of decommissioning standards proposed by the DECC will be shown below, established in order to meet the international obligations, guarantee safe navigation, meet needs of users of the sea and protect the environment.

- All disused installations and structures must be totally removed from the ocean as total removal of installation allows the marine environment to be used again for other purposes.
- Life extension and repowering are encouraged if they are demonstrated to be profitable but anyhow at the moment the wind farm is no longer in use it must be dismantled.
- All operations are focused towards the dismantling of all installations and bringing them to shore to reuse, recycle or dispose components.
- There are many exceptions to the complete removal of structures and other solutions may be accepted, after having carefully evaluated each case:
 - o Structures being reused whether they will be reused for renewable energy purposes or not. Examples:
 - a. Cabling reused for new renewable energy installations
 - b. Test site for wave and tidal energy devices
 - c. Breakwater with integrated wave energy device
 - o Foundations and structures below seabed level: if the depth is enough to prove they are not a hazard for the marine environment and since the removal of whole foundations could cause significant negative impacts and big disruptions on the environments, as well as being an expensive and dangerous operation, they may be left in place, ensuring the remains do not become uncovered.
 - o Cabling: when proved they are buried at an appropriate depth and the risks of being exposed are low. Cable burial should be monitored during the life and beyond the life of the farm.
 - o Scour protection materials: allowed to be left in-situ to preserve marine habitats that may have arisen over the life of the installation, as long as they do not have a disruptive impact on the environment, safe navigation or conservation aims.
- The decision to allow parts of the installation to stay in place will be made after studying the following points;
 - o Effects on the safety of navigation
 - o Impact on other users of the sea
 - o Effect on the marine environment and living resources
 - o Costs of removal
 - o Risks of injury to personnel in case of removal
- Sea bed must be cleaned in accordance with the decommissioning programs. Its cleansing must be verified. The area must be monitored after the decommissioning.
- The area that must be cleaned of debris, inspected and verified after the decommissioning depends on each case, following mostly the guidance for O&G structures: the minimum area to be covered is a radius of 500 m around any installation.

- Methods or procedures are also influenced case by case, depending on the site and the nature of installation. Removal techniques are expected to develop as experience is gained and technologies evolve, so only a few recommendations can be made.
 - The method of removal will be the BPEO (Best Practicable Environmental Option): *“option which provides the most benefit or least damage at the environment as a whole, at an acceptable cost in both long and short term”*. In other words, the chosen final solution will be a balance between the reduction of environmental risks and the viability and costs of reducing these risks.
 - The method of removal must assure the safety of navigation on the surface and on the subsurface, and the safety for other uses of the sea, in addition to compliment the general safety and health considerations.

5 ECONOMICAL ASPECTS

Companies operating the wind farms will be the ones in charge of dismantling them. From their point of view that is a cost to be assumed in the future. To assure that decommissioning activities will be correctly held, usually governments require operators to pay a deposit in advance (at the time of construction or during the years of operation, prior to dismantling), to ensure operation will take place even though the company has become insolvent by that time. The amount of the bound will be the result of the expected total decommissioning costs.

5.1 SUMMARY OF COSTS

As said in sections earlier, planning is an important part of the decommissioning program that can decrease the costs substantially. Experiences until present day show that usually the decommissioning costs entail a 50-60% of the installation costs, but they are expected to lower as experience in the field is gained. (Topham & McMillan, 2016). The operator DNV-GL estimated that dismantling costs may range between 200.000 and 600.000 € per turbine. A breakdown of the costs is shown on *Figure 27*.

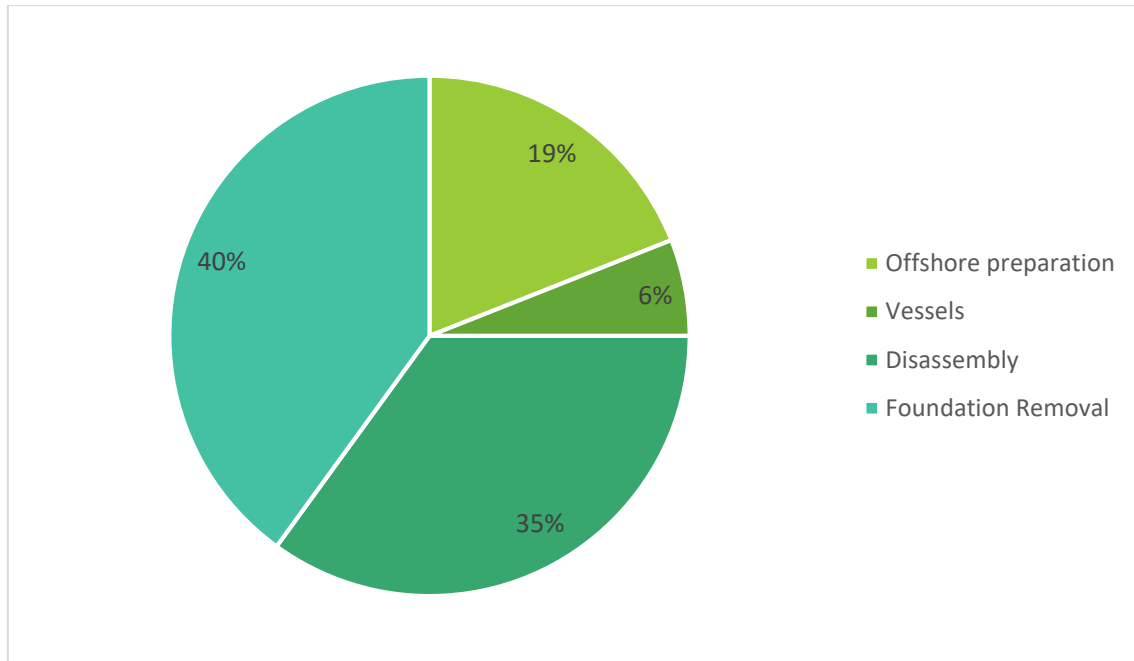


Figure 27. Decommissioning costs breakthrough. Source: Climate Change Capital (2017)

Having said that, it may be possible that in the short term, re-powering the wind farm is much more beneficial than dismantling straight at the end of its lifetime. In terms of costs, keeping the turbine in prolonged time operation will increase the maintenance costs and the risks of structural failures, but it will increase the revenues; while decommissioning the farm at the end of its lifetime saves on costs but means no additional gains either (Jensen, 218). Be that as it may, particular studies for each wind farm will be held, conducting research for structural fatigue and financial safety.

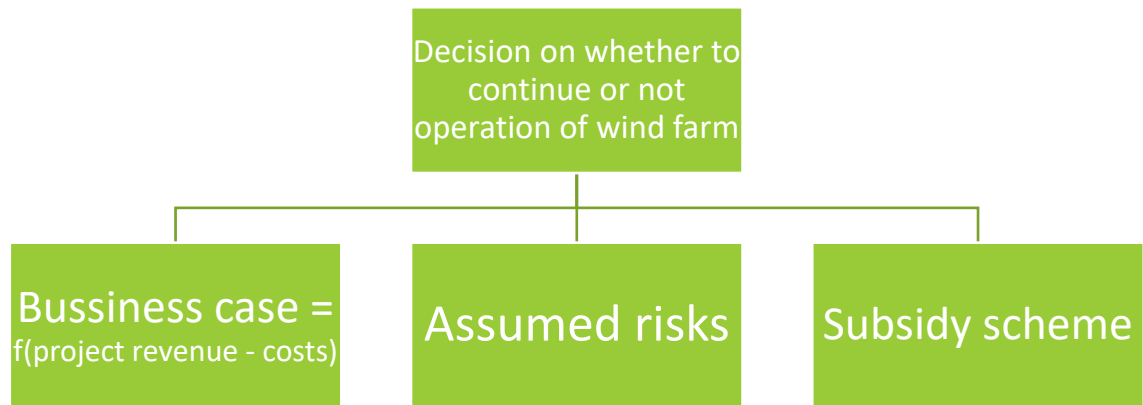


Figure 28. Influential decision-making factors on continuing operation of wind farm. Source: Own illustration.

The economical costs include the cost of decommissioning, monitoring and maintenance, and technical issues like possibility of re-powering; but it is not the only cost that will face the project. Also, environmental costs related to the diversity, biomass and impact on marine environment should be taken into consideration, or costs related to social areas, such as impacts on commercial fishing, recreational industries or public access. A modelling for the decommissioning costs only including technical issues of turbine and foundation removal stages is presented on the following section.

5.2 MODELLING OF DECOMMISSIONING COSTS

Model by Kaiser & Snyder (2012)

i. Turbine removal:

The total time is a summation of the time needed to achieve all operations: the travel time of the vessel from port to the location, the removal of the turbines, the loading time, and the travel time between the turbines.

MODEL 1: Self-transportation model

In this first model all stages are assumed to be performed independently and by separate vessels, assuming a self-propulsion.

- Travel time of the vessel (in hours):

$$Travel (TT) = 2 \frac{D}{S}$$

Where:

- D: Distance to port
- S: Speed of vessel

- Time needed to perform complete removal of turbines per trip (in hours):

$$Removal (RT) = VC \times R$$

Where:

- VC: *Vessel capacity*
- RT: *Time needed to remove a turbine*

- Time needed to load the turbines onto the vessel (in hours):

$$Loading (LT) = VC \times L$$

Where:

- L: *Offloading time per turbine*
- Taking into account the vessel has to move between turbines in field (in hours):

$$Moving (MT) = VC \times M$$

Where:

- M: *Needed time to move between the turbines*

Finally, the total time per trip, in hours:

$$TPT = TT + RT + LT + MT$$

Now, taking into consideration that vessels are not always able to work, a correction factor “weather” which accounts for the percentage of time the weather delays the operations.

$$Adjusted\ time\ per\ trip\ (AT) = TPT \times \frac{1}{W}$$

Also, as the total number of turbines may exceed the capacity of the used vessel, the number of needed trips must be computed:

$$Number\ of\ trips\ (NT) = \frac{number\ of\ turbines}{VC}$$

Finally, the total time needed to remove the turbines (in hours) is calculated by means of the following equation:

$$RemovalTime = AT \times NT$$

Now the costs are represented in terms of time and must be transformed to monetary daily cost (€/day):

$$Total\ daily\ cost\ (TDC) = SDR + VDR$$

Where:

- SDR: *Spread day rate*. Cost that takes to hire a crew for one day.
- VDR: *Vessel day rate*. Cost per day of hiring a vessel.

Finally, now it is possible to calculate total costs of the removal of turbines:

$$Cost\ Turbines\ (CT) = \frac{RemovalTime}{24} \times TDC$$

MODEL 2: Multi vessel transportation model

In this study case, a transportation support barge is assumed to carry out all transportation operations, so there are no logistical constraints. The total time of removing a turbine is the sum of time needed to remove it and the time to transport it to another location.

$$Removal\ (RT) = R + M$$

Where:

- R: *Removal time*
- M: *Moving time*

Adjusted time per turbine:

$$Adjusted\ time\ per\ turbine\ (AT) = RT \times \frac{1}{W}$$

So the time of removing all turbines of the installation:

$$TTURB = AT \times number\ of\ turbines$$

Finally, the total monetary cost is obtained by multiplying the total removal time by the total daily cost:

$$Cost\ Turbines\ (CT) = \frac{RemovalTime}{24} \times TDC$$

ii. **Foundation removal**

MODEL 1: Single-vessel

In this model a SPIV or jackup vessel is expected to perform all cutting and lifting operations of the removal a monopile foundation. Total time and total costs are computed per foundation and on the basis that comprises the following times:

- Stabilization of the vessel on the site (*Stab*)
- Preparation for decommissioning (*Prep*)
- Cutting of foundation (*Cut*)
- Time of lifting foundation and placing it on a barge (*Lift*)
- Time to move to next foundation (*Move*)

$$T_{FOUND} = Stab + Prep + Cut + Lift + Move$$

$$Cost\ Foundation\ (CF) = (VDR + SDR) \times \frac{FC}{TC} \times T_{FOUND}$$

Where:

- FC: *Farm capacity* (MW)
- TC: *Turbine capacity* (MW)
- $\frac{FC}{TC}$ = *number of units in the farm*

MODEL 2: Offshore support vessel

In the OSV method, multiple vessels are used for decommissioning the monopile. A support vessel will be used to support the cutting operations and a lift vessel will arrive on site after the cutting of the foundation, reducing that way the total amount of time requires.

Time required the removal of one foundation includes:

- Stabilization time at site
- Time to lift foundation and place on barge
- Time to jack vessel down and move to next foundation

$$TF_{removal} = Stab + Lift + Move$$

Next equation presents the time required to cut the foundation, involving the preparation, the cutting and the stabilization time.

$$TF_{cut} = Stab + Prep + Cut + Move$$

$$Cost\ Foundation = TF_{removal} \frac{FC}{TC} \times (VDR + SDR) + TF_{cut} \times \frac{FC}{TC} \times ODR$$

Where:

- ODR: *Daily cost of the Offshore Support Vessel* (€/day)

iii. Other

There are no existent models for estimating other costs, including removal of cables, scour protection, substations and meteorological towers, so they will be roughly approximated in a case-by-case approach by the accessible data.

6 CONCLUSIONS

In the first place, I think it is safe to say that offshore wind power has emerged as a combination of the best characteristics of offshore oil and gas and onshore wind industries, being both two sectors with years of experience behind their backs. Offshore wind energy means much bigger turbines, ergo much more power, and that makes worth it investing in advances and perfecting techniques, converting offshore wind energy in a highly motivating and interesting growing area. Probably offshore wind energy is one of the most powerful sectors to-be in the next decades, and the fact that to this day only three offshore fixed wind farms have been completely dismantled and the first offshore floating farm dismantling is planned for 2043, proves that as a quite big challenge. All along this project, though, we have seen how lack of clear governmental coordination and, in general, lack of regulations have been a recurrent topic in all sections. Even if the perspective of the years to come is thrilling, this absence of homogeneity in actions or at the time of making decisions turns all the concepts into something a little bit ambiguous and confusing; overshadowing the future forecasts. Hence, it is of great concern to highlight the need for unified criteria and standards as in any other construction field.

The second conclusion we can extract is uncertainties and risk-assuming dominate the process of dismantling, that is irrefutable since we are working in open ocean. We must simply accept it is something we cannot fight against or control, neither in short or long term. Nature will continue to be unpredictable and it is a price we must assume. However, what we can do achieve is to ensure we are making a good planification of the whole process. Carrying out a decommissioning plan at early stages can reduce significantly the costs and risks, so the second lesson to learn is the importance of anticipating the decommissioning since the very beginning of the construction phase.

In fact, decommissioning is not that much as a stranger. Often it is simply defined as the inverse process of installing a wind farm, but *easier*. The same level of care as in installation procedures is not needed during decommissioning, which implies less needed time and less expected costs. Anyhow, maintaining some standards is necessary, and especially if components are to be reused, since they will need to be preserved in good conditions. Also, to cut expenses on procedures or equipment would backfire, as it is likely to compromise the safety of the process. All operations must be carried out in a controlled manner, carefully loading the components onto the barges and unbolting them if necessary. Even though nowadays the re-using of components is not very common, it is expected to be a very plausible alternative as technologies evolve, or at least it should. Decommissioning a wind farm is a big responsibility, not only because of the preservation of the marine environment but in terms of material waste. The quantity of obsolete components generated after the removal is huge and must be consequently treated. As re-using is not quite an option yet, recycling should be the alternative, but we are face the same problem as stated before: there is a lot of experience with the recycling of steel but other materials are still not that straightforward, and wind farms are formed by a quite large variety of materials. Recycling is a present issue in most of the decommissioning plans but it is not mandatory yet, again, due to the lack of regulations. Research on how to be able to re-use and recycle more materials must be carried out in order to make these options much more attractive and to decrease the associated costs so it eventually becomes profitable. There is no point in the exploitation of renewable energies if we are not able to find a way to reduce the carbon footprint of the elements which make them up. Also, any potential hazardous or pollutant materials that may appear should be carefully treated during all removal operations.

During the lifetime of the farm the area where is placed will suffer alterations. Dismantling is directed towards trying to reduce the impact of the farm operation in that area, by removing all components and leaving the marine environment clean and free of any generated debris, in conditions as close as possible as before the whole installation. Although it is not permitted to abandon entire structures in-situ, a balance between the impacts of removing them completely and the impact of leaving some buried parts shall be considered. The farms are expected to operate for 20 to 30 years and within this time marine habitats are likely to develop around the components, and all major disturbances that may interfere with the ecosystem should be avoided.

In addition, life-extension should be also studied before shutting entirely down the farm. It is expected that new technologies will have developed by the time we need to start making decisions about re-powering or not, so we are not able still to say if it will eventually become a plausible solution.

To sum up, as in any civil engineering project, there is no universal solution that will fit all cases. Each wind farm must be approached in its own way and on the basis of its particular needs and the available resources, both technical and financial.

What is clear is that the future of offshore wind energy has a promising appearance.

7 REFERENCES

Publications, Books and Journal Articles

- Aloys Nghiem, Pineda, I., Nghiem, A., Pineda, I., Aloys Nghiem, & Pineda, I. (2017). Wind energy in Europe: Scenarios for 2030. *Wind Europe*, (September), 32.
- Amador, J. (2000). Analisis de los parametros tecnicos en la aplicacion de los sistemas de informacion geografica a la integracion regional de las energias renovables en la produccion descentralizada de electricidad. *Doctor*, (January 2000), 270.
- Boyle, G. (2012). *Renewable energy: power for a sustainable future* (3rd ed.). Oxford University Press.
- Broadbent, I., & Strachan, P. (2015). UK government puts offshore wind at risk. *Energy Post*, (January).
- Bulder, B. (2016). Lifecycle and de-commissioning offshore wind, (March), 1–28.
- Butterfield, S., Jonkman, J., & Sclavounos, P. P. (2005). Engineering Challenges for Floating Offshore Wind Turbines By, 10. <https://doi.org/http://dx.doi.org/10.1016/j.jog.2014.02.003>
- Byrne, B., & Houlsby, G. (2013). Halb_Log_mm_Papier.pdf, 1–21. <https://doi.org/10.1098/rsta.2003.1286>
- Campos, A., Molins, C., Gironella, X., & Trubat, P. (2016). Spar concrete monolithic design for offshore wind turbines. *Proceedings of the Institution of Civil Engineers - Maritime Engineering*, 169(2), 49–63. <https://doi.org/10.1680/jmaen.2014.24>
- Climate and Pollution Agency, Agency, C. and P., & Climate and Pollution Agency. (2011). Decommissioning of offshore installations, 25–35. <https://doi.org/10.1098/rspb.2006.3551>
- Department of Energy and Climate Change, Change, D. of E. and C., & Department of Energy and Climate Change. (2011). Decommissioning of offshore renewable energy installations under the Energy Act 2004. *Guidance Notes for Industry, 2011*(January), 66.
- EWEA. (2015). The European offshore wind industry key trends and statistics 1st half 2015. (January), 31. <https://doi.org/10.1109/CCA.1997.627749>
- Forstner, S. E. U., & Murphy, R. (n.d.). (Environmental Engineering) G Simpson (auth.), Prof. D. G. Gorman, Dr. J. Neilson (eds.)-Decommissioning Offshore Structures-Springer-Verlag London (1998).
- Gonzalez-Rodriguez, A. G. (2017). Review of offshore wind farm cost components. *Energy for Sustainable Development*, 37, 10–19. <https://doi.org/10.1016/j.esd.2016.12.001>

- Guezuraga, B., Zauner, R., & Pölz, W. (2012). Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy*, 37(1), 37–44.
<https://doi.org/10.1016/j.renene.2011.05.008>
- Ho, A., Mbistrova, A., & Corbetta, G. (2016). The European offshore wind industry key 2015 trends and statistics. *European Wind Energy Association*, (February), 31.
<https://doi.org/10.1109/CCA.1997.627749>
- Jackson, D., & Stone, D. (n.d.). Best Practicable Environmental Option (BPEO) studies in support of decommissioning projects in the UK are discussed. *Enviros*, 1–5. Retrieved from <http://irpa11.irpa.net/pdfs/6h8.pdf>
- Jensen, J. P. (2018). Evaluating the environmental impacts of recycling wind turbines. *Wind Energy*, (September), 1–11. <https://doi.org/10.1002/we.2287>
- Kaiser, M. J., & Snyder, B. F. (2012). Offshore wind energy cost modeling: Installation and decommissioning. *Green Energy and Technology*, 85. <https://doi.org/10.1007/978-1-4471-2488-7>
- Kaiser, M. J., & Snyder, B. F. (2012). *Offshore Wind Energy Cost Modeling*.
<https://doi.org/10.2174/97816080528511120101>
- Kerkvliet, H. (2015). *Offshore wind farm decommissioning: Introducing a multi-criteria decision approach*. Uppsala University.
- Lange, B., Aagaard, E., Andersen, P.-E., Moller, A., Niklasson, S., & Wickman, A. (1999). Offshore wind farm Bockstigen: installation and operation experience. *Ewec-Conference*, 25, 300–303.
- Mokhtar, H. K. M., & Haitham K. M. Mokhtar. (2014). Decommissioning of Offshore Platforms. *Oil and Gas Decommissioning*, 1(1), 2–44.
- Multon, B. (2012). *Marine renewable energy handbook*. John Wiley & Sons.
- Oil&Gas UK. (2018). Decommissioning insight.
- Ostachowicz, W., McGugan, M., Schröder-Hinrichs, J.-U., & Luczac, M. (2011). *MARE-WINT New Materials and Reliability in Off shore Wind Turbine Technology. Proceedings of the 9th International Seminar on Speech Production (ISSP 2011)*.
<https://doi.org/10.1007/978-3-319-39095-6>
- Pearson, D. (2006). Decommissioning Wind Turbines In The UK Offshore Zone, 27–29.
- Perveen, R., Kishor, N., & Mohanty, S. R. (2014). Off-shore wind farm development: Present status and challenges. *Renewable and Sustainable Energy Reviews*, 29, 780–792.
<https://doi.org/10.1016/j.rser.2013.08.108>
- Peyrard, C. (2016). OFFSHORE WIND TURBINE FOUNDATIONS - EDF R&D - LNHE.
- Pineda, I., & Pierre Tardieu, W. (2018). Annual combined onshore and offshore wind energy statistics. <https://doi.org/10.1016/j.preghy.2016.08.046>

- Pineda, I., & Tardieu, P. (2017). The European offshore wind industry. *Wind Europe*, (January), 33. <https://doi.org/10.1007/s10551-010-0634-7>
- Smith, G., Michael, D., Paul, R., Arlene, W., Chris, G., John, H., ... Chris, E. (2016). Assessment of Offshore Wind Farm Decommissioning Requirements - Ontario Ministry of the Environment and Climate Change, (May).
- Strach-Sonsalla, M., Stammler, M., Wenske, J., Jonkman, J., & Vorpahl, F. (2016). Offshore wind energy. *Springer Handbook of Ocean Engineering*, (2012), 1267–1285. https://doi.org/10.1007/978-3-319-16649-0_49
- The European offshore wind Energy Association. (2013). Key trends and statistics 2013, (January).
- The European offshore wind Energy Association. (2012). Key trends and statistics 2012, (January).
- Topham, E., & McMillan, D. (2017). Sustainable decommissioning of an offshore wind farm. *Renewable Energy*, 102, 470–480. <https://doi.org/10.1016/j.renene.2016.10.066>
- Weinzettel, J., Reenaas, M., Solli, C., & Hertwich, E. G. (2009). Life cycle assessment of a floating offshore wind turbine. *Renewable Energy*, 34(3), 742–747. <https://doi.org/10.1016/j.renene.2008.04.004>
- Wilkes, J., Moccia, J., Arapogianni, A., Dragan, M., Plytas, N., & Genachte, A.-B. (2012). The European offshore wind industry key 2011 - trends and statistics, (January), 31. <https://doi.org/10.1109/CCA.1997.627749>
- Wind, T. E., & EWEA. (2010). The European offshore wind industry - key trends and statistics 2009, (January), 1–14. <https://doi.org/10.1109/CCA.1997.627749>

Web Pages

- 4COffshore. Bockstigen Offshore Wind Farm. Retrieved from <https://www.4coffshore.com/windfarms/bockstigen-sweden-se02.html>
- AGCI. Wind. Retrieved from <https://www.agci.org/data/articles/wind>
- BCG. Preparing for the Next Wave of Offshore Decommissioning. Retrieved from <https://www.bcg.com/publications/2018/preparing-for-next-wave-offshore-decommissioning.aspx>
- BennetOffshore. Liftboat design. Retrieved from <http://www.bennettoffshore.com/seps.html>
- BSEE. Reef In Place. Retrieved from <https://www.bsee.gov/what-we-do/environmental-focuses/decommissioning/reef-in-place>

CorporateVattenfall. The first decommission in the world of an offshore wind farm is now complete. Retrieved from <https://corporate.vattenfall.com/press-and-media/press-releases/2016/the-first-decommission-in-the-world-of-an-offshore-wind-farm-is-now-complete/>

CPH. FALLING COSTS & TECH INNOVATIONS WILL DRIVE OFFSHORE WIND POWER BOOM. Retrieved from <https://cph.world/2017/01/27/falling-costs-tech-innovations-will-drive-offshore-wind-power-boom/>

DOSITS. How is sound used to research wind energy? Retrieved from <https://dosits.org/people-and-sound/examine-the-earth/how-is-sound-used-to-research-wind-energy/>

DTI. GENVIND. Retrieved from <https://www.dti.dk/genvind/35154>

GTM. World's First Offshore Wind Repowering Completed in Sweden. Retrieved from <https://www.greentechmedia.com/articles/read/worlds-first-offshore-wind-repowering-completed-in-sweden#gs.rzjXGNqv>

HOWaT. Grid Connection. Retrieved from http://www.esru.strath.ac.uk/EandE/Web_sites/16-17/WindAndTidal/gridConnection.html

NewEnergyUpdate. Offshore operators act on early decommissioning data to limit costs. Retrieved from <http://newenergyupdate.com/wind-energy-update/offshore-operators-act-early-decommissioning-data-limit-costs>

offshoreWIND. Swedish Offshore Wind Farm Is No More. Retrieved from <https://www.offshorewind.biz/2018/10/04/swedish-offshore-wind-farm-is-no-more/>

Orsted. World's first offshore wind farm now dismantled. Retrieved from <https://orsted.com/en/Media/Newsroom/News/2017/09/Worlds-first-offshore-wind-farm-now-dismantled>

PowerTechnology. Full circle: decommissioning the first ever offshore windfarm.

ReFiber. ReFiber. Retrieved from <http://www.refiber.com/history.html>

StateOfGreen. Dissection of wind turbine blades for the GENVIND project. Retrieved from <https://stateofgreen.com/en/partners/state-of-green/news/dissection-of-wind-turbine-blades-for-the-genvind-project/>

TheWindPower. Bockstigen Offshore (Sweden). Retrieved from https://www.thewindpower.net/windfarm_en_10313_bockstigen-offshore.php

TheWindPower. Sweden wind farms database. Retrieved from https://www.thewindpower.net/store_country_en.php?id_zone=17

Windpower. How DONG Energy dismantled the world's first offshore wind farm. Retrieved from <https://www.windpowerengineering.com/projects/offshore-wind/dong-energy-dismantled-worlds-first-offshore-wind-farm/>

Windpower. Decommissioning - Should they stay or should they go? Retrieved from
<https://www.windpowermonthly.com/article/1349270/decommissioning-stay-go>

Windpower. "First" offshore repowering completed. Retrieved from
<https://www.windpoweroffshore.com/article/1520172/gallery-first-offshore-repowering-completed>

WorldSteel. Steel solutions in the green economy. Wind turbines. Retrieved from
<https://www.worldsteel.org/en/dam/jcr:41f65ea2-7447-4489-8ba7-9c87e3975aab/Steel+solutions+in+the+green+economy:+Wind+turbines.pdf>